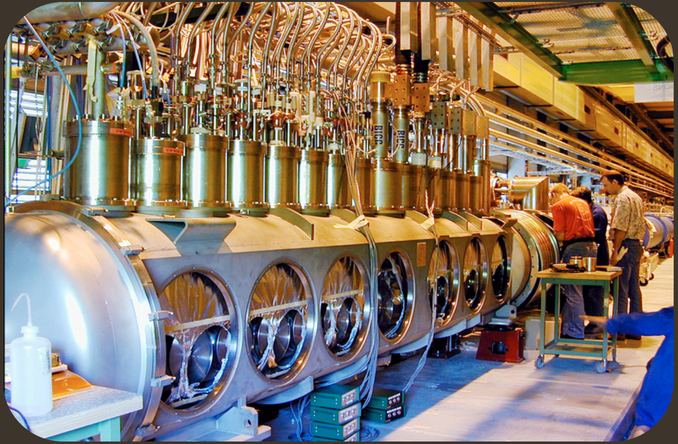
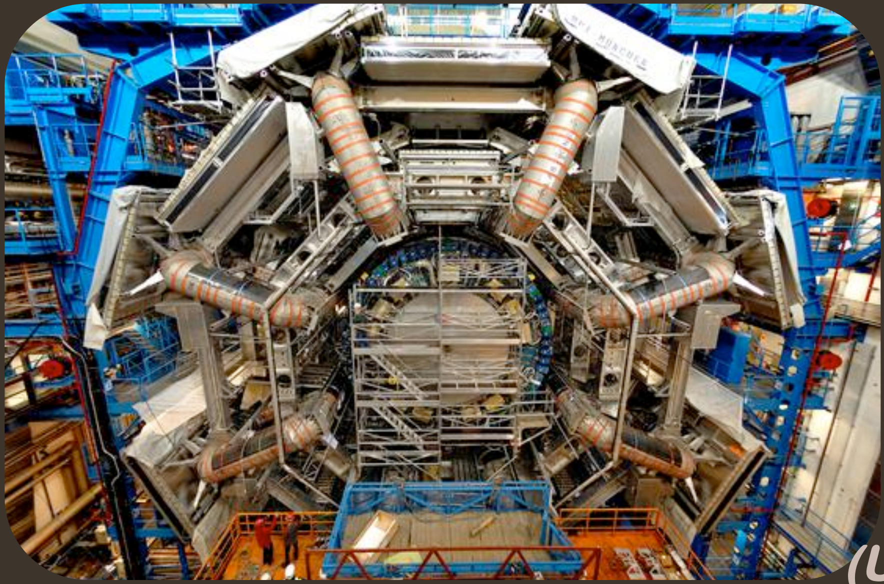
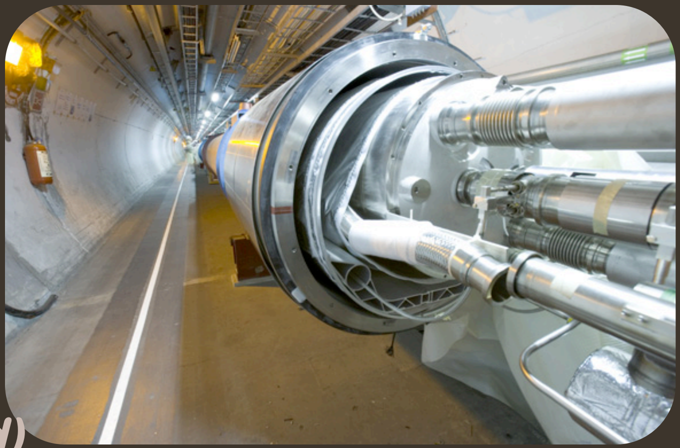


*IOP HEPP*
*2009*

# Supersymmetry Searches in Trilepton Final States with the ATLAS Detector at the LHC, CERN

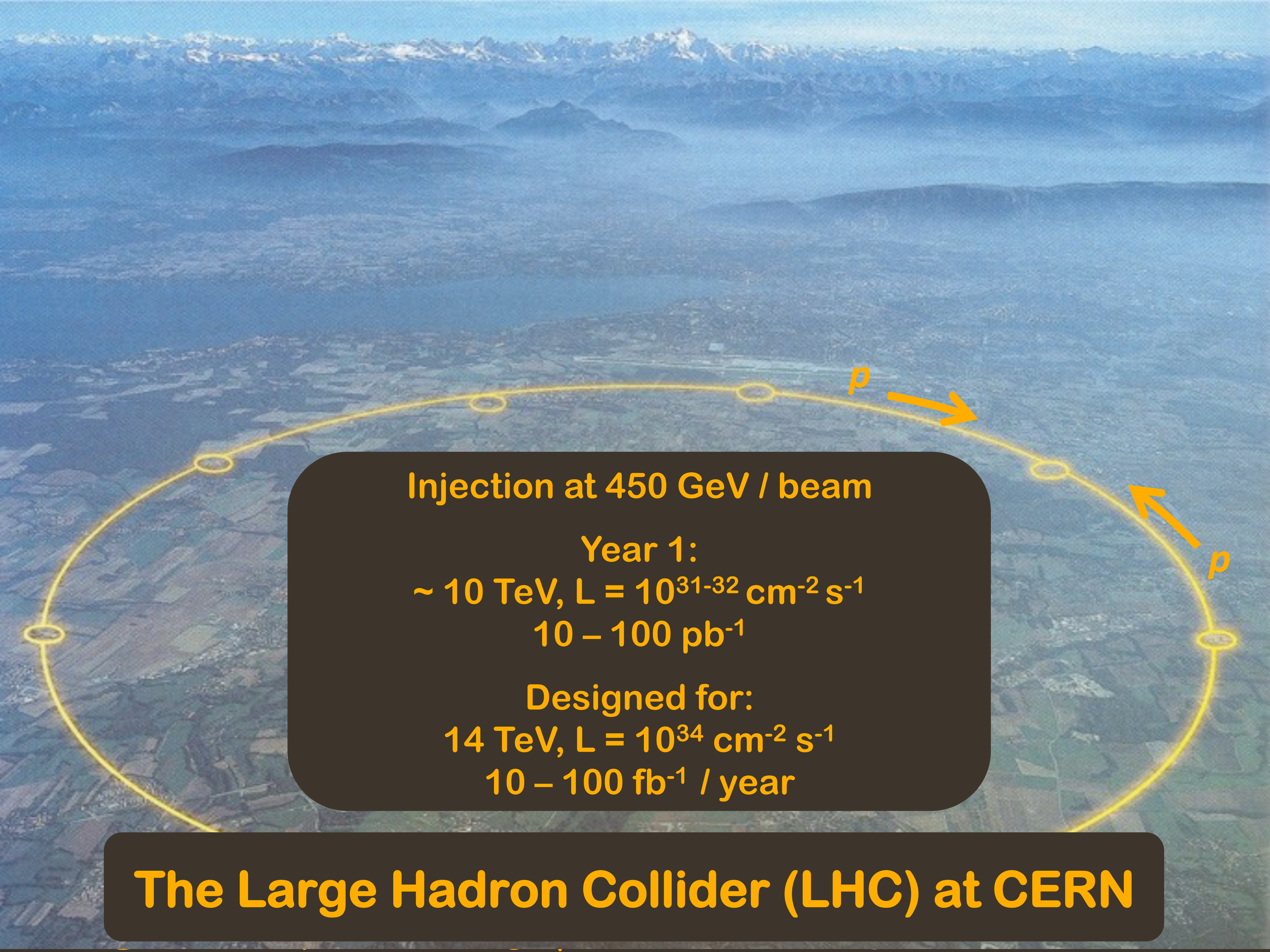


*Oleg Brandt,*
*3rd year*
*(Univ. of Oxford)*



# Today's Menu

- The Large Hadron Collider (LHC)
- ATLAS
- Introduction:
  - Why trilepton final states?
- The trilepton search:
  - Main backgrounds
  - Selection
  - Results:
    - Discovery reach of ATLAS
    - Systematics
  - Trigger strategy
  - Measuring the rate of leptons from heavy flavour decays
- Summary
- Outlook




Injection at 450 GeV / beam

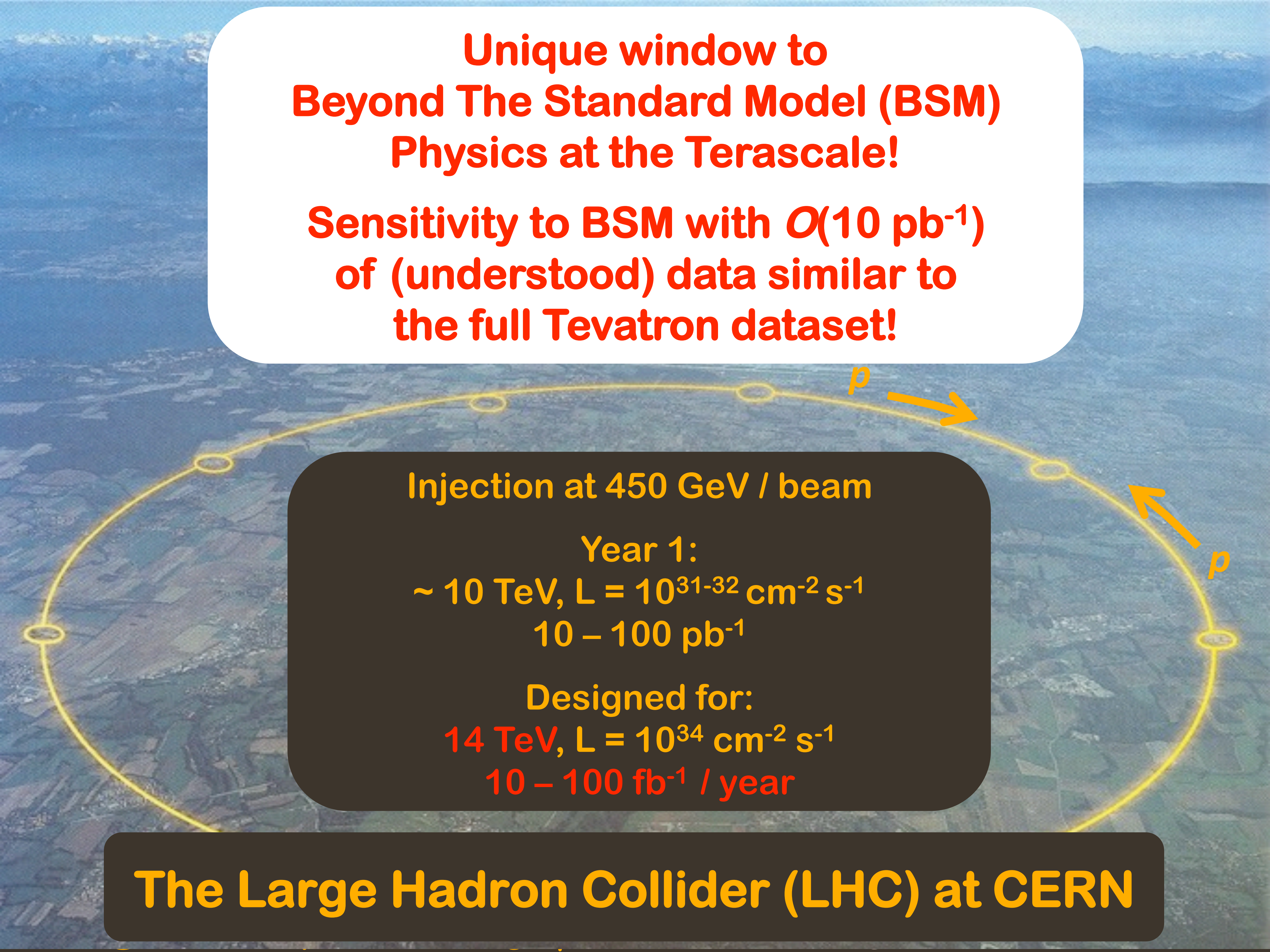
Year 1:
~ 10 TeV, $L = 10^{31-32}\ cm^{-2}\ s^{-1}$
10 – 100 $pb^{-1}$

Designed for:
14 TeV, $L = 10^{34}\ cm^{-2}\ s^{-1}$
10 – 100 $fb^{-1}$ / year

# The Large Hadron Collider (LHC) at CERN

## Unique window to Beyond The Standard Model (BSM) Physics at the Terascale!

## Sensitivity to BSM with $\mathcal{O}(10\ \mathrm{pb}^{-1})$ of (understood) data similar to the full Tevatron dataset!

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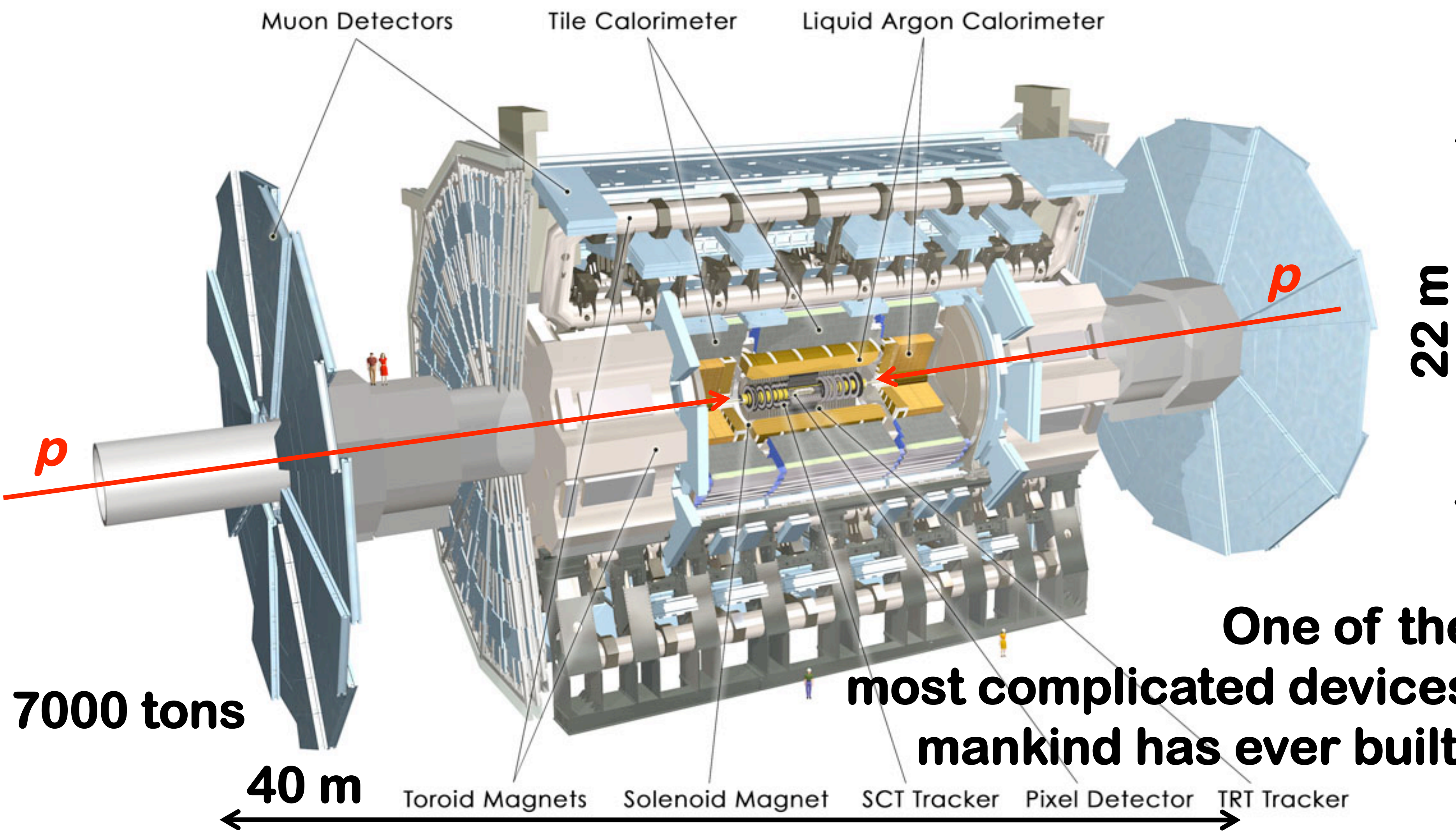
# The Large Hadron Collider (LHC) at CERN

# The ATLAS Experiment

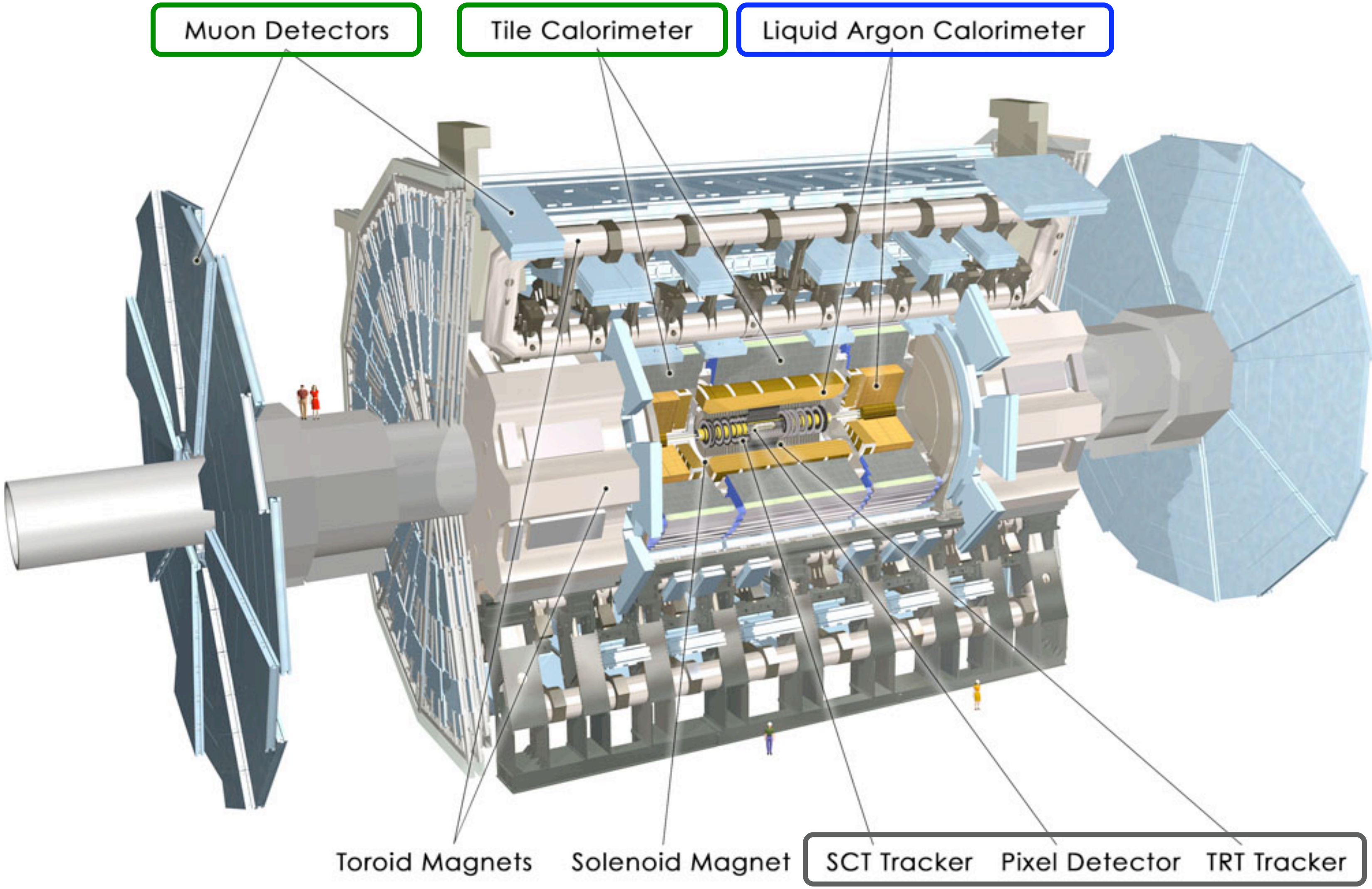
**Mast head: 2604 scientists!**




**7000 tons**

**One of the most complicated devices mankind has ever built!**

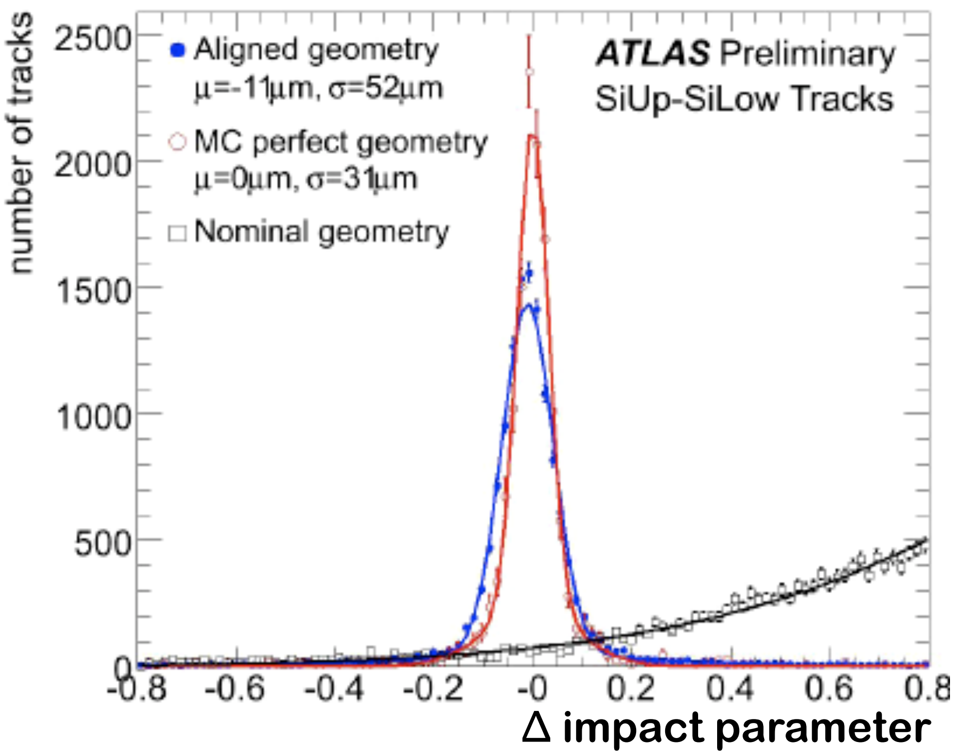
# ATLAS (Slightly More Technical)



# Alignment of the ATLAS Silicon Tracker

*(the 2nd and 3rd year of my Ph.D.)*

- ATLAS took cosmics between Sept. and Dec. 2008 (M8+)
- High-quality first-pass alignment with cosmic data:



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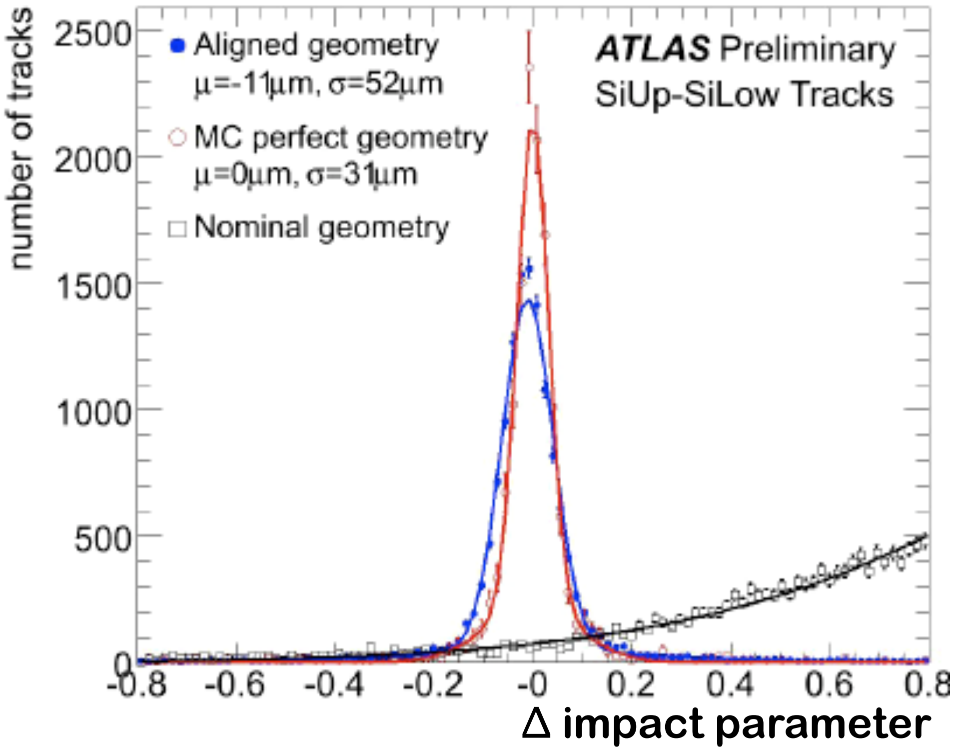
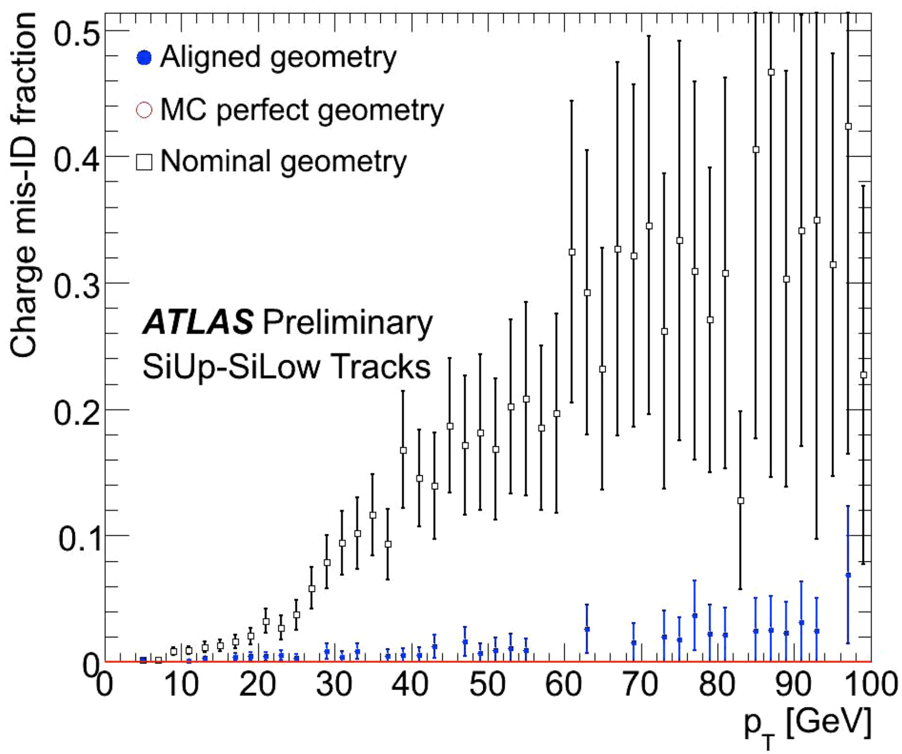
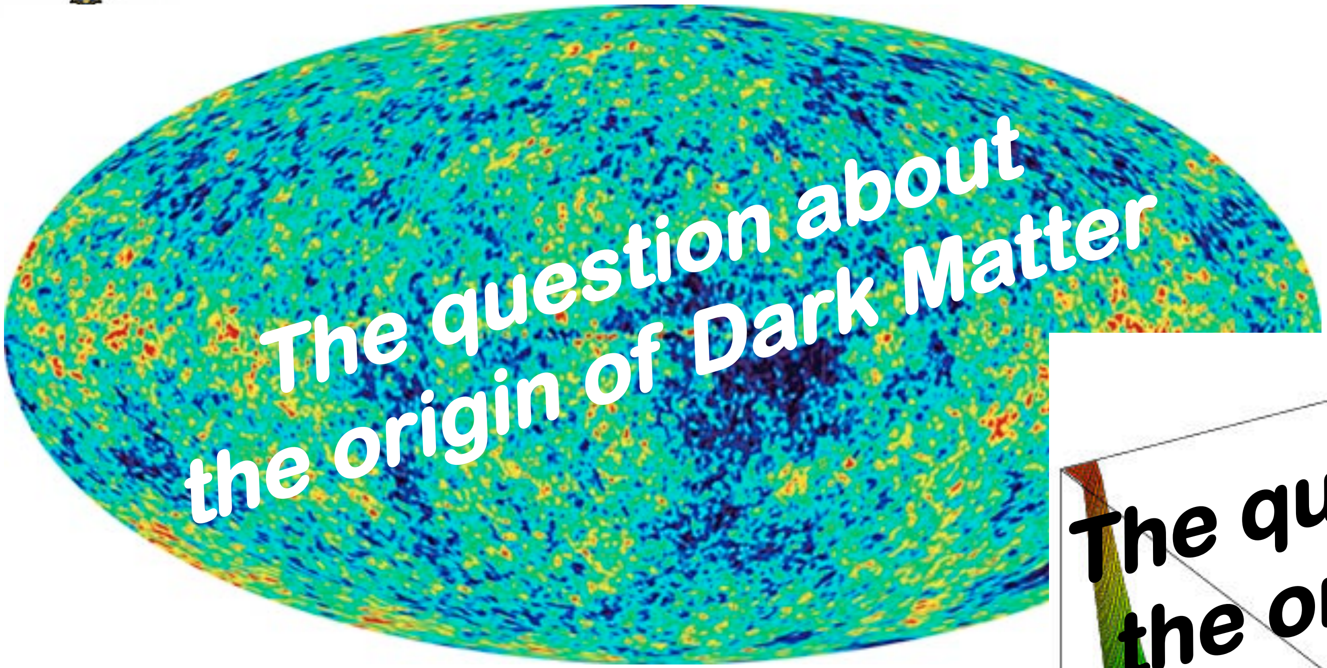


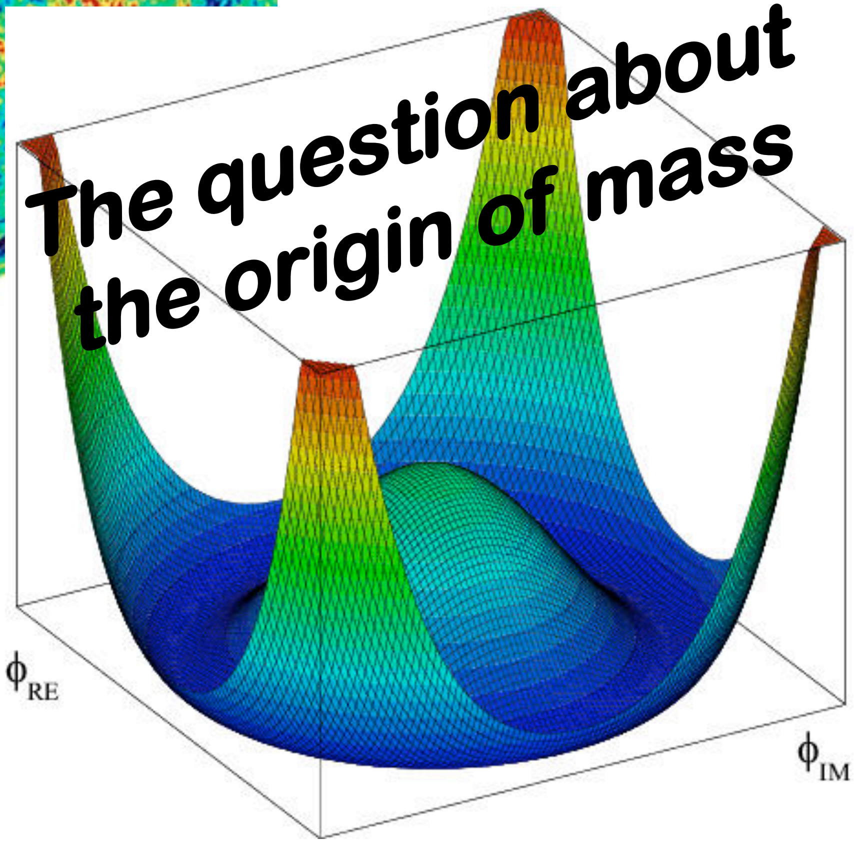




- However, a lot of work still needs to be done!

# Why Trilepton Final States?
## Is It a No-Lose BSM Search?




**Questions I want to address:**



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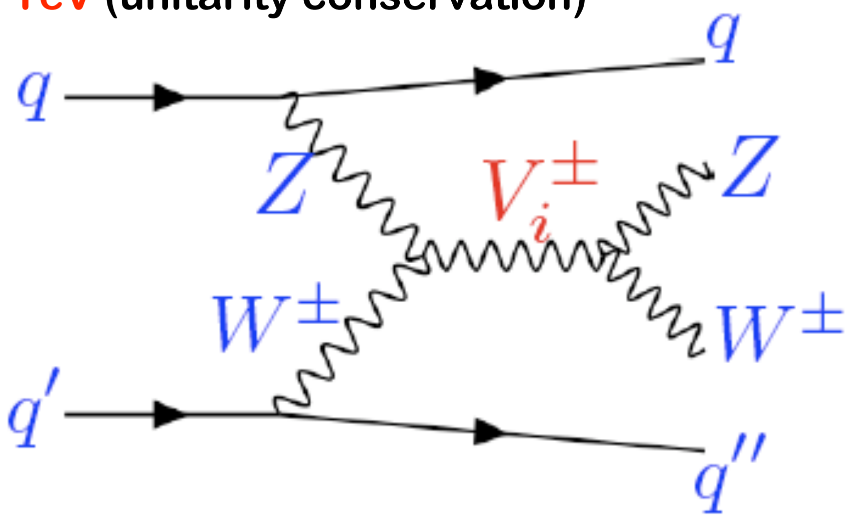
## Is It a No-Lose BSM Search?

- Origin of mass?
  - At the moment, the Higgs mechanism is widely accepted
  - If no Higgs:
    - Diboson scattering X-section must increase dramatically!
      - At ~1 TeV (unitarity conservation)



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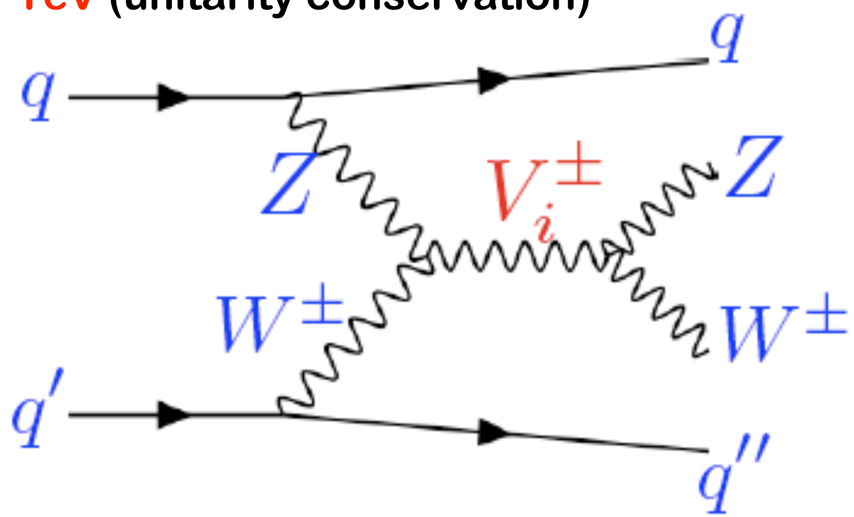


    - Tri-lepton + missing $E_T$ final states ideal (*WZ* production):
      - Discovery mode at the Tevatron!
      - *(did not look explicitly into it)*
    - Due to high boost of *WZ*, *l* + 2*j* is an interesting signature, too

# Why Trilepton Final States? (III)
## Is It a No-Lose BSM Search?

- Origin of Dark Matter?
  - If there is a Higgs:
    - Hierarchy problem (non-cancelling virtual loop corrections)
      - Fine tuning at $10^{-32}$ level!

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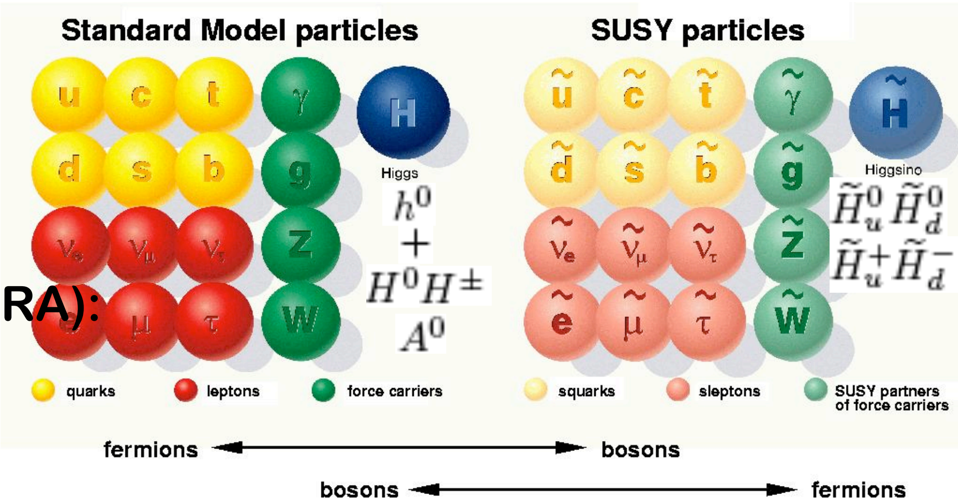
    - *Lightest Supersymmetric Particle* (LSP): Dark Matter!
    - *R*-parity conserving models
    - Minimal Supergravity (mSUGRA):
      - 5 parameters



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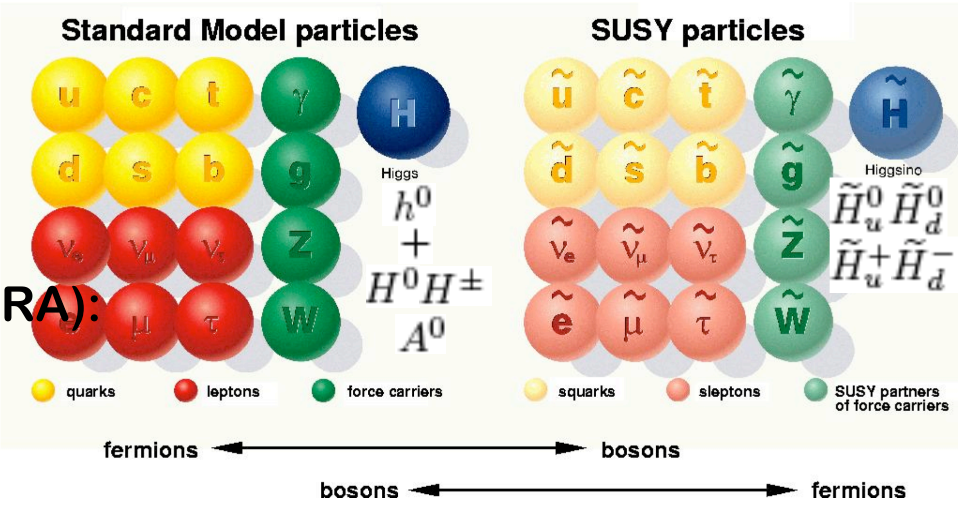
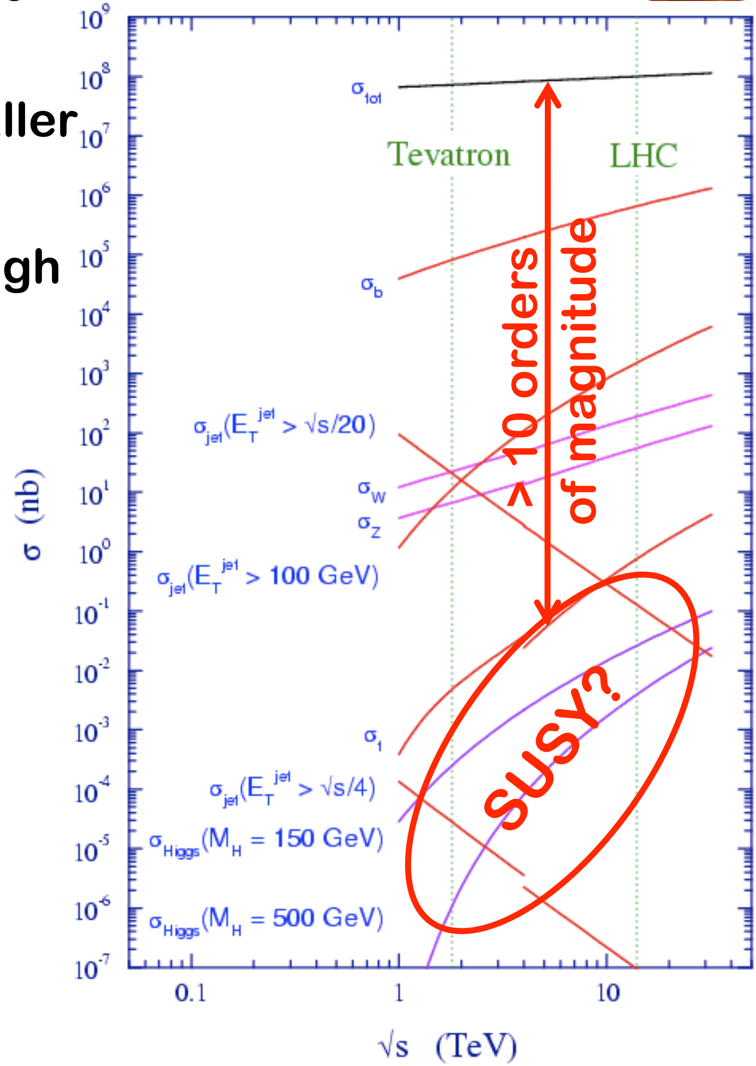



  - Trilepton + missing $E_T$
    - Important SUSY window!
    - Especially if strong sparticle production suppressed:
      - Not necessarily the case in mSUGRA type of models at ATLAS
    - Don’t only look under the lamppost!

# Why Are Leptonic Final States Interesting for BSM Searches?

- Leptons can be used to reject QCD junk at the LHC:
  - Trigger level:
    - Lepton rates intrinsically much smaller
  - Offline analysis level:
    - Significantly less data to plow through



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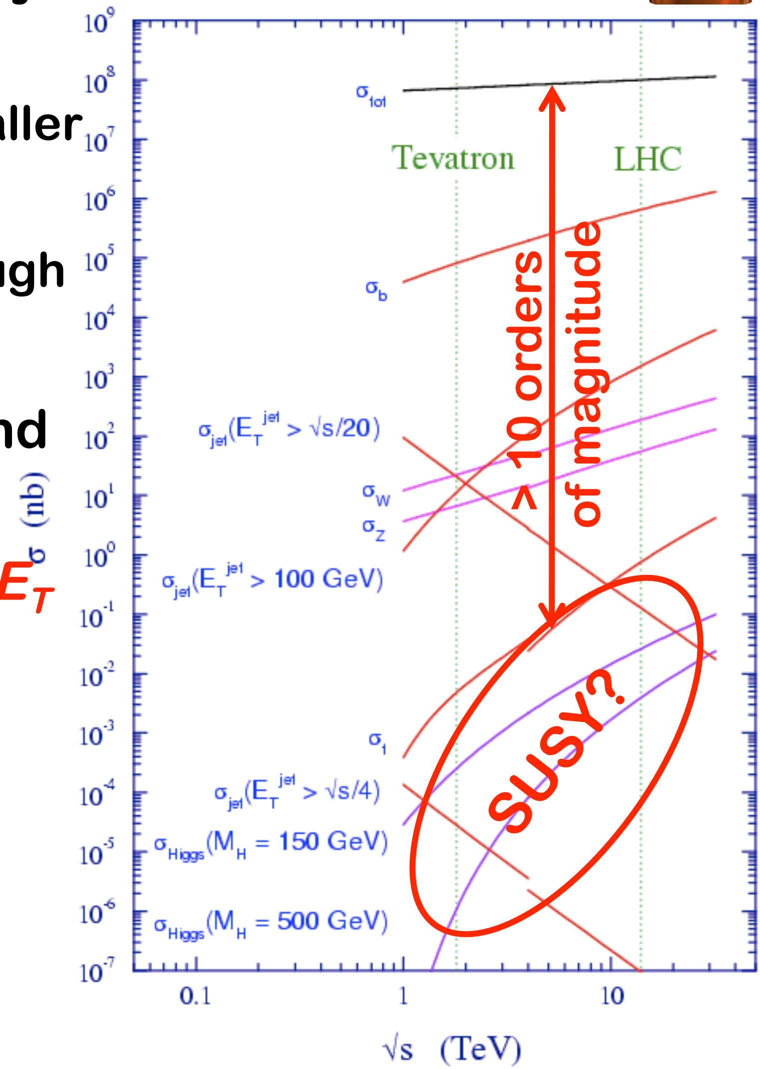

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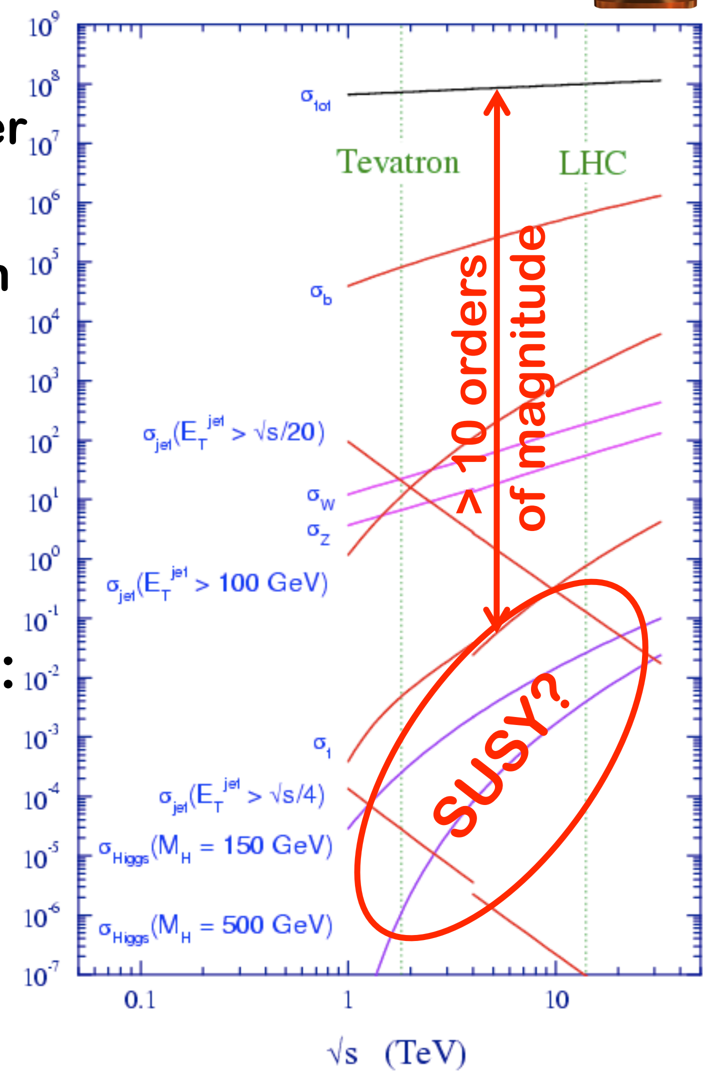

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- Once BSM discovered use leptons to:
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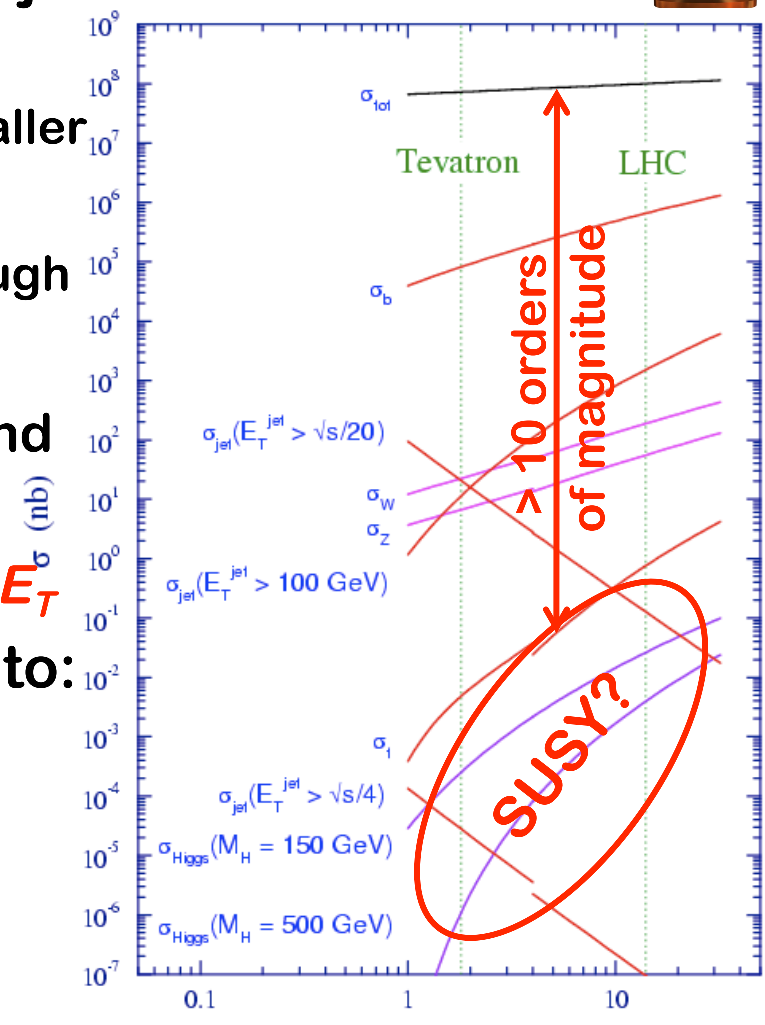
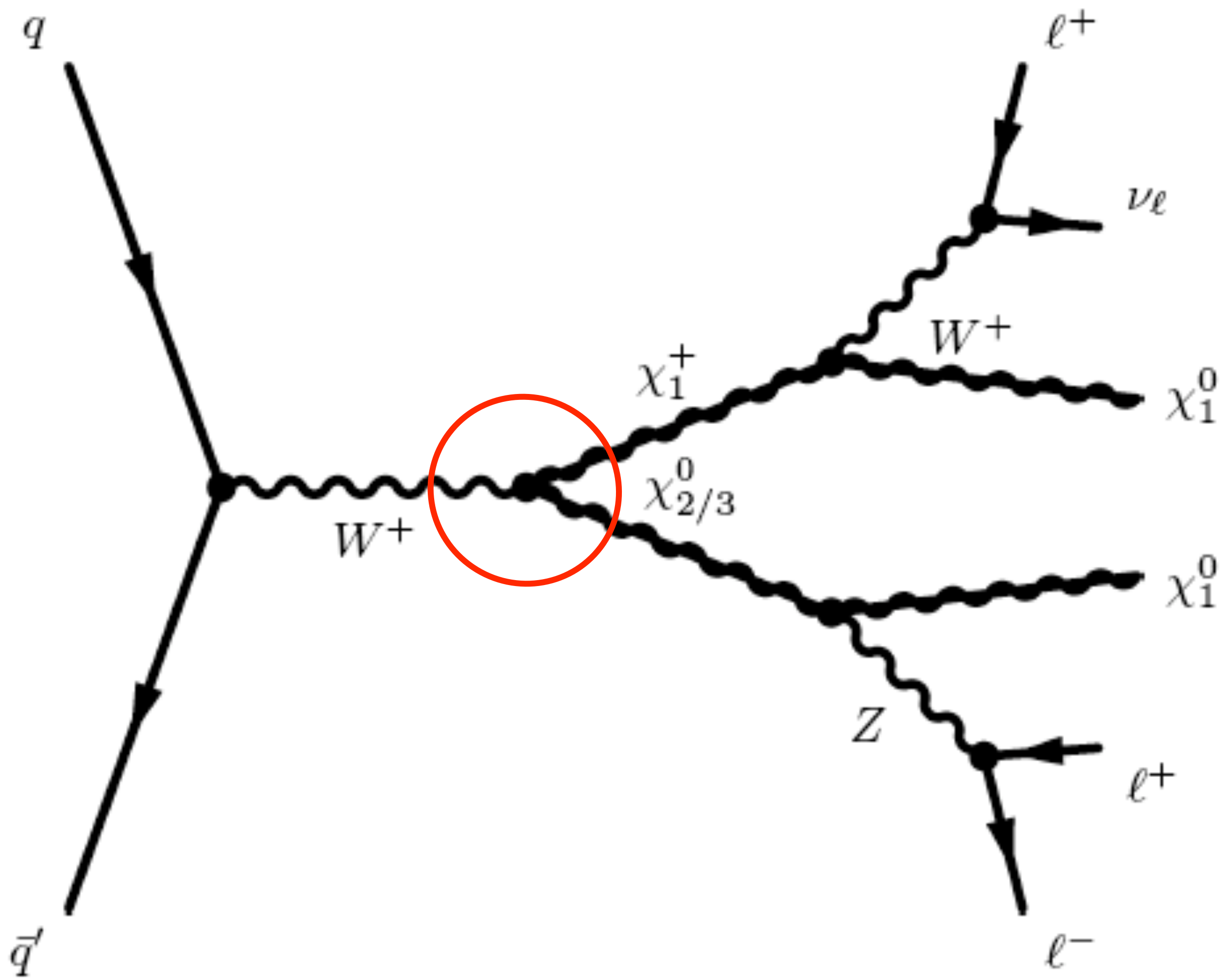
  - Measure particle spectrum
- However:
  - Typically smaller X-sections
  - Track / calo isolation to reject leptons from heavy flavour!



# Trilepton + Missing $E_T$ Signal

- In the context of SUSY, we *primarily* search for associated chargino-neutralino pair-production:



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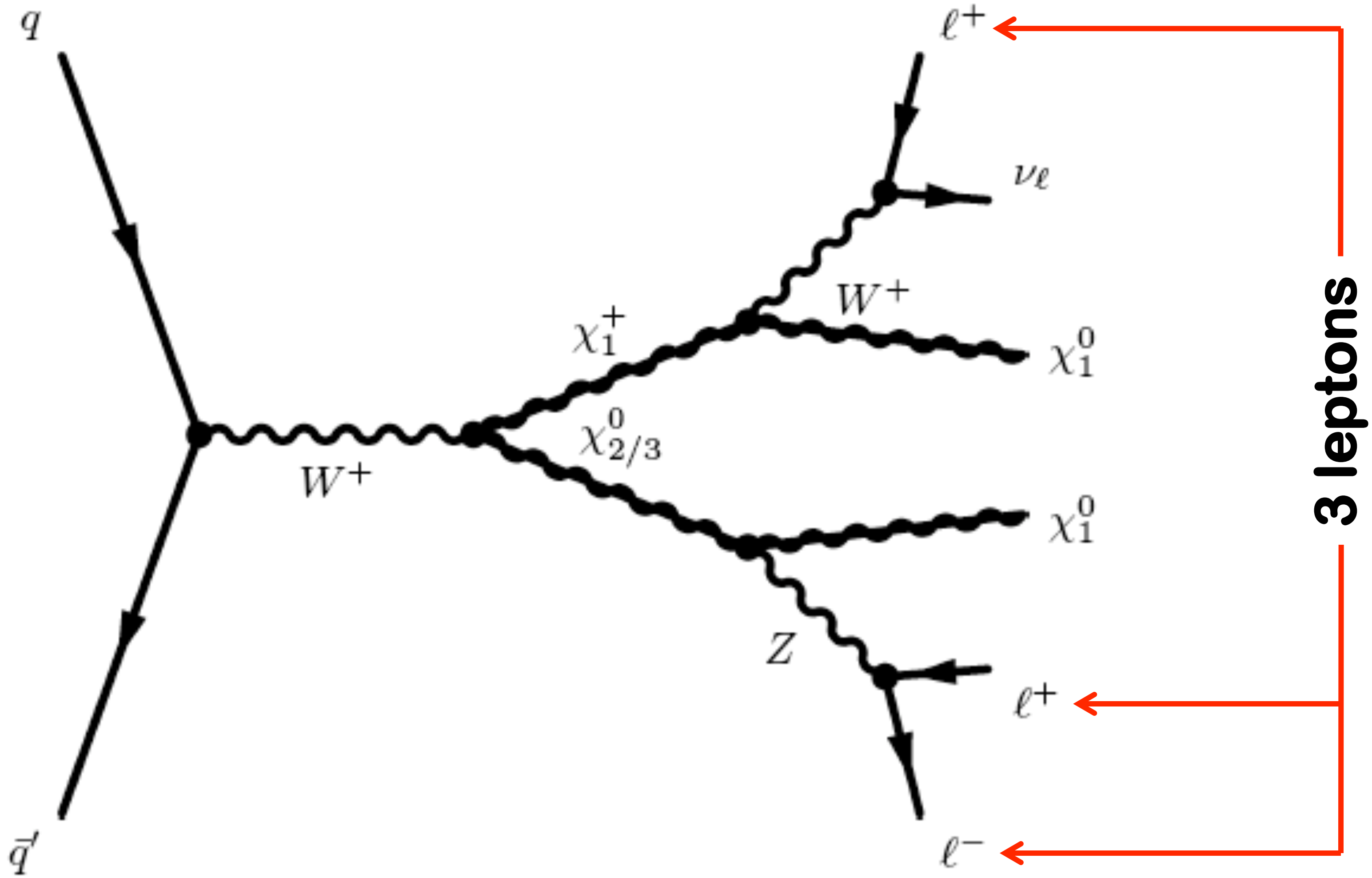

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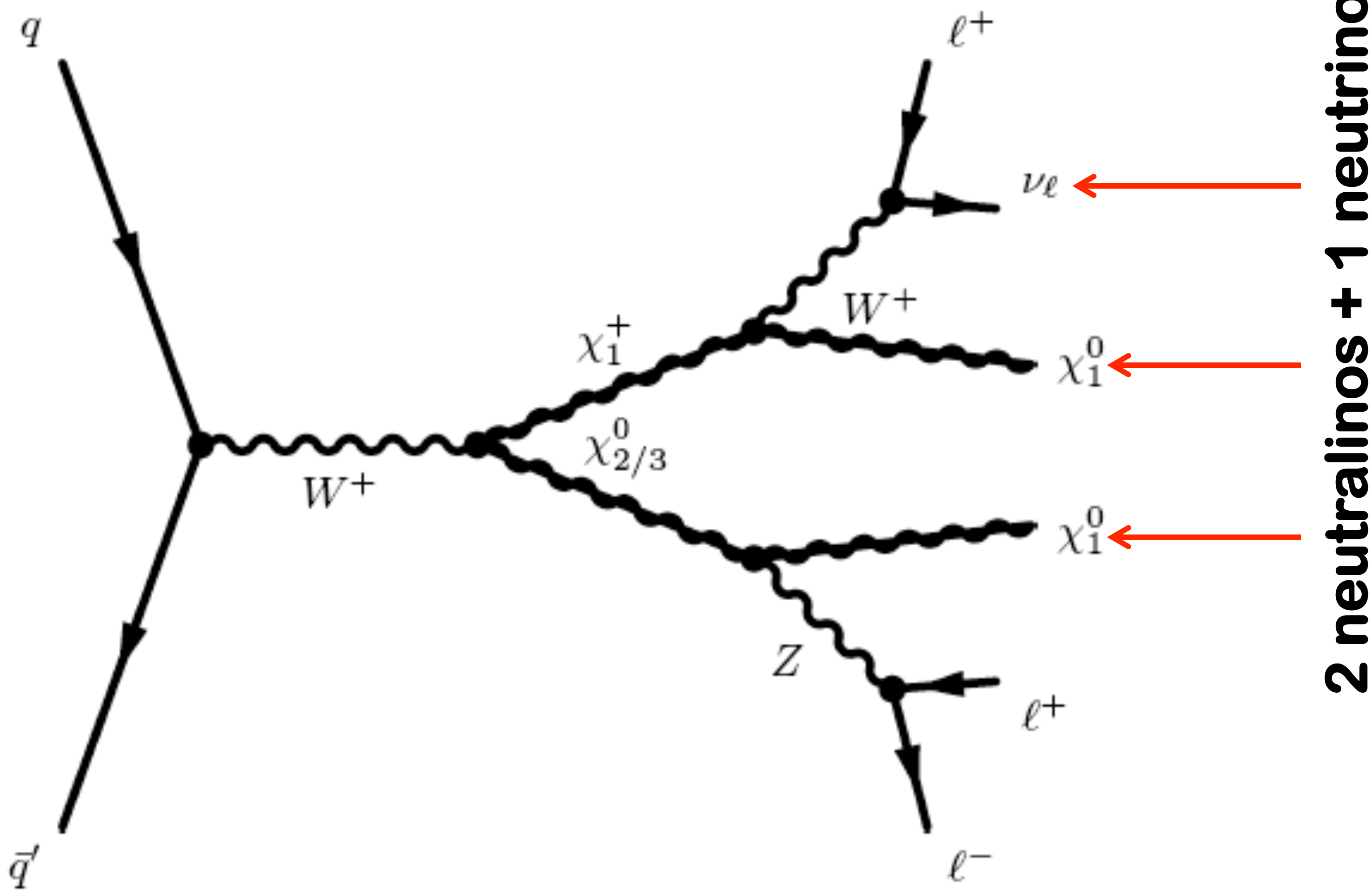
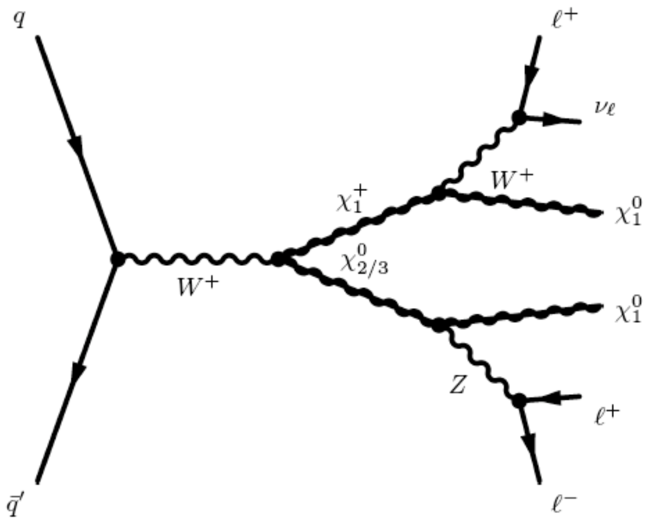


# Trilepton + Missing $E_T$ Signal

- Optimise the trilepton + missing $E_T$ search for the most difficult scenario:




Models with low hadronic X-sections:
e.g. models with high *O*(3 TeV)
strong interacting sparticle masses,
e.g. in the "focus point" region SU2:

$m_0 = 3550$ GeV, $m_{1/2} = 300$ GeV,
$A_0 = 0$, $\tan\beta = 10$, $\mu > 0$.

- Also sensitive to many other BSM models!
  - In SUSY context:
    - Long decay chains typical for the "bulk" region

# Trilepton + Missing $E_T$: Backgrounds

- Backgrounds with >= 3 prompt leptons:
  - *WZ, ZZ*:
    - Relatively high lepton $p_T$, genuine missing $E_T$ for *WZ*
    - X-section only *O*(10) higher than SUSY

[arXiv:0901.0512]

| Process | $\sigma$ [pb] | $k$ factor | $\langle w \rangle$ | $\int dt\, \mathcal{L}$ [fb$^{-1}$] |
|---|---|---|---|---|
| $WW$ | 24.5 | 1.67 | 1 | 1.22 |
| $WZ$ | 7.8 | 2.05 | 1 | 2.98 |
| $ZZ$ | 2.1 | 1.88 | 1 | 12.7 |
| $Z\gamma$ | 2.6 | 1.30 | 1 | 2.98 |
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    - Additional lepton from b-decay
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- Cuts:
  - Lepton preselection: $p_T$ > 10 GeV, |η| > 2.5
  - At least one lepton pair
  - At least one OSSF pair with $20\ \mathrm{GeV} < M_{OSSF}$
  - 3rd lepton (highest $p_T$)
  - Track isolation:
    - e: $p_{T\,\mathrm{track,max}}^{\Delta R=0.2} < 2\ \mathrm{GeV}$
    - μ: $p_{T\,\mathrm{track,max}}^{\Delta R=0.2} < 1\ \mathrm{GeV}$
  - No OSSF pair with:
    $81.2\ \mathrm{GeV} < M_{OSSF} < 102.2\ \mathrm{GeV}$
  - $E_{\mathrm{T}}^{\mathrm{miss}} > 30\ \mathrm{GeV}$
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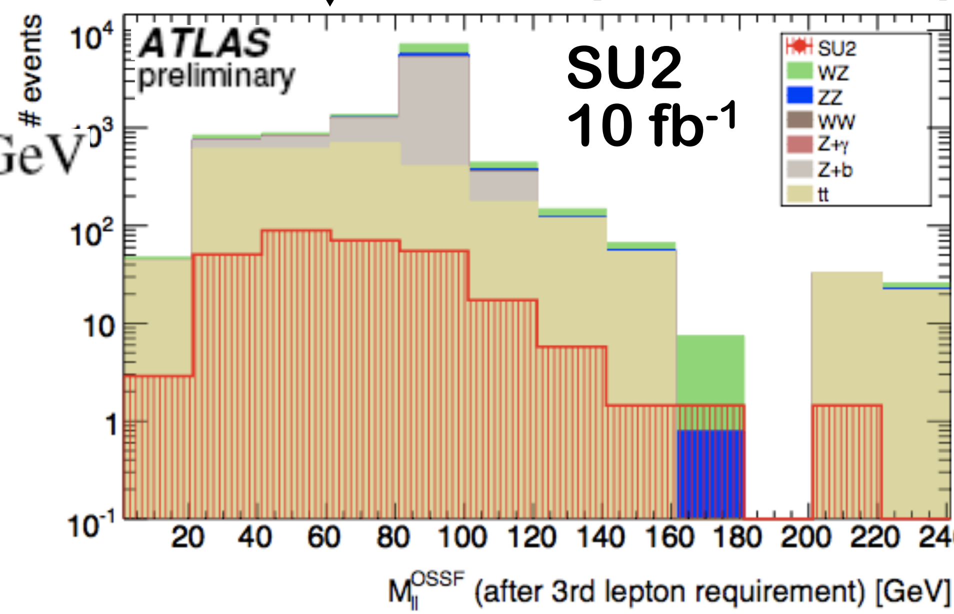
*after this cut*

[arXiv:0901.0512]



# Track and Calorimeter Isolation

- After requirement of a 3rd lepton:
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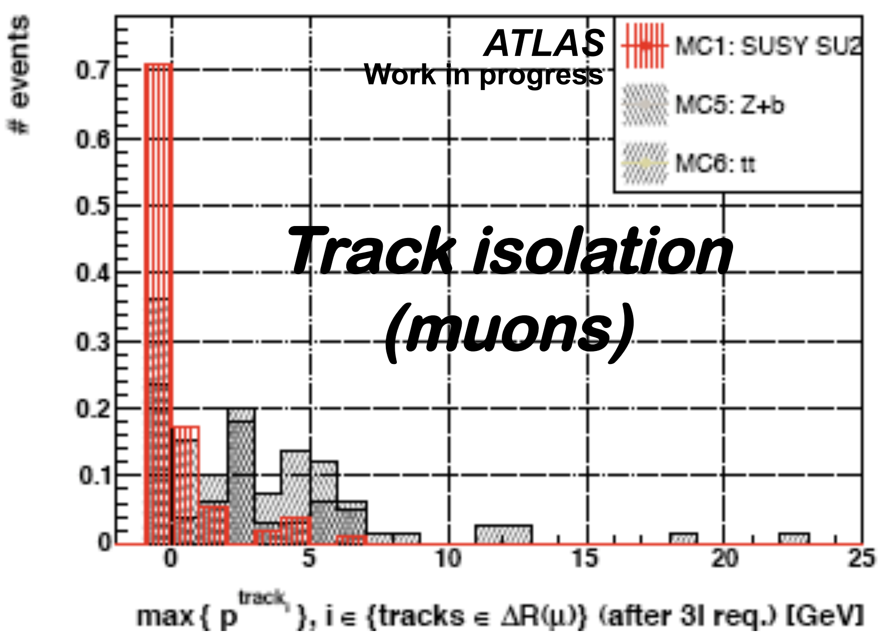
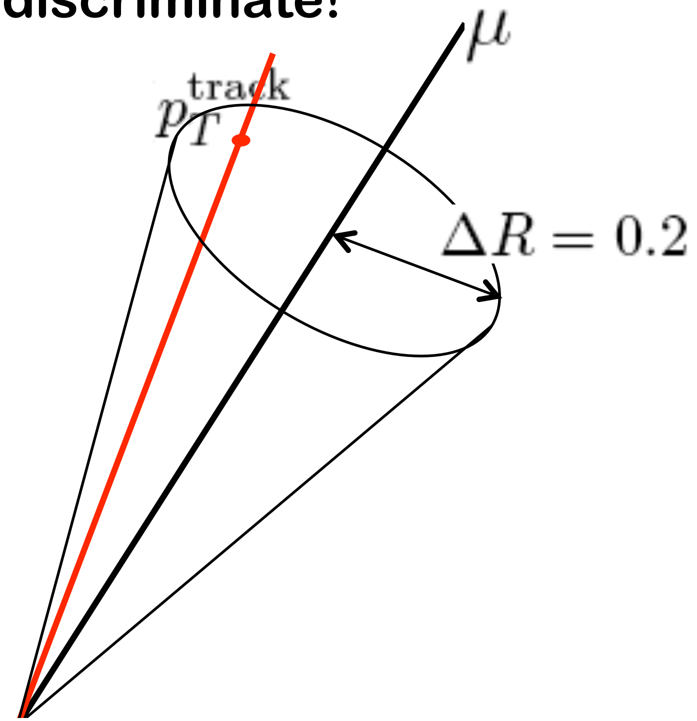
  - Expect additional activity around such leptons
  - Use track and calorimeter isolation to discriminate!




$$I_{0.2}^{\rm trk}(\ell) \equiv \max{}_{i,j}\{p_T^{{\rm track}_i}|{\rm track}_i \in \Delta R(\ell_j)\} \text{ where } \ell = \mu, e$$

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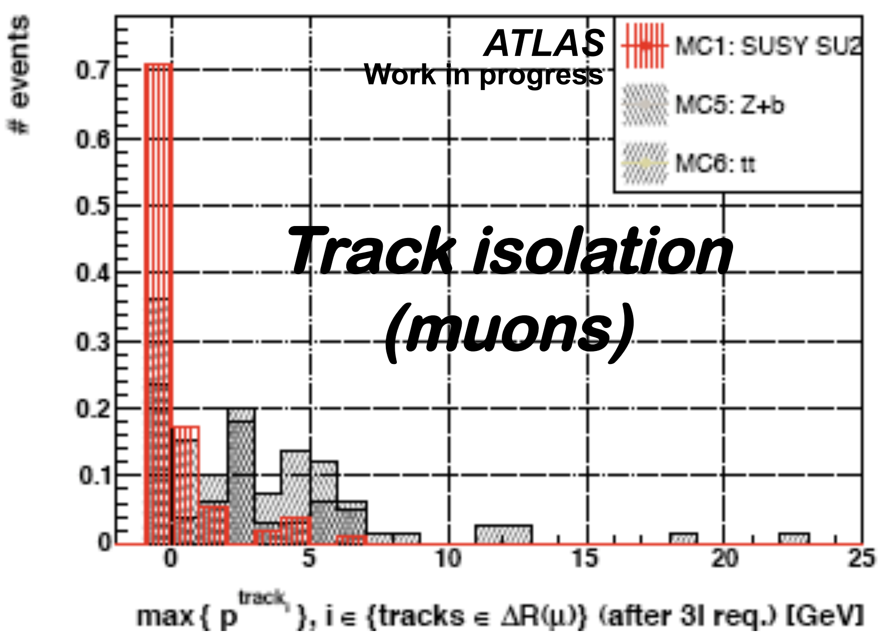


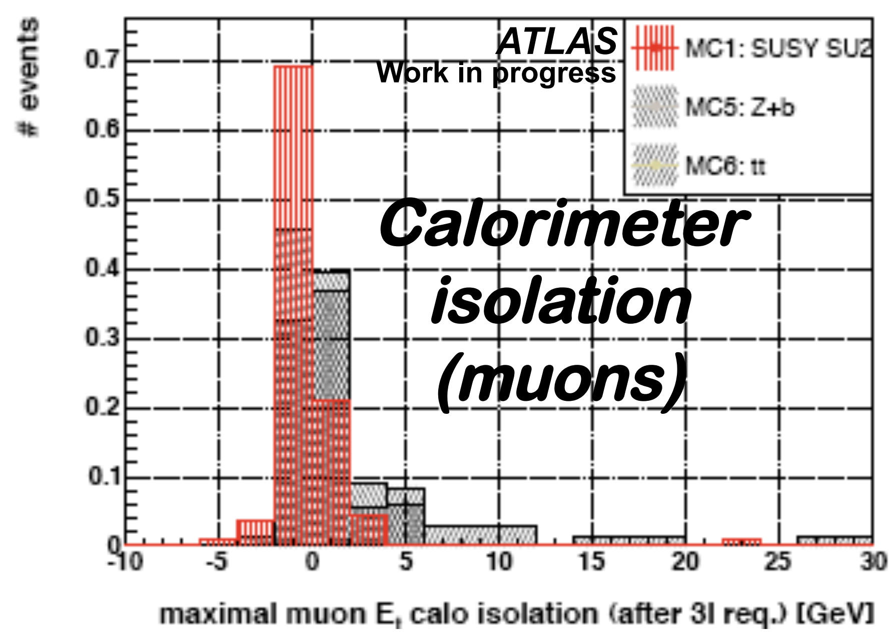

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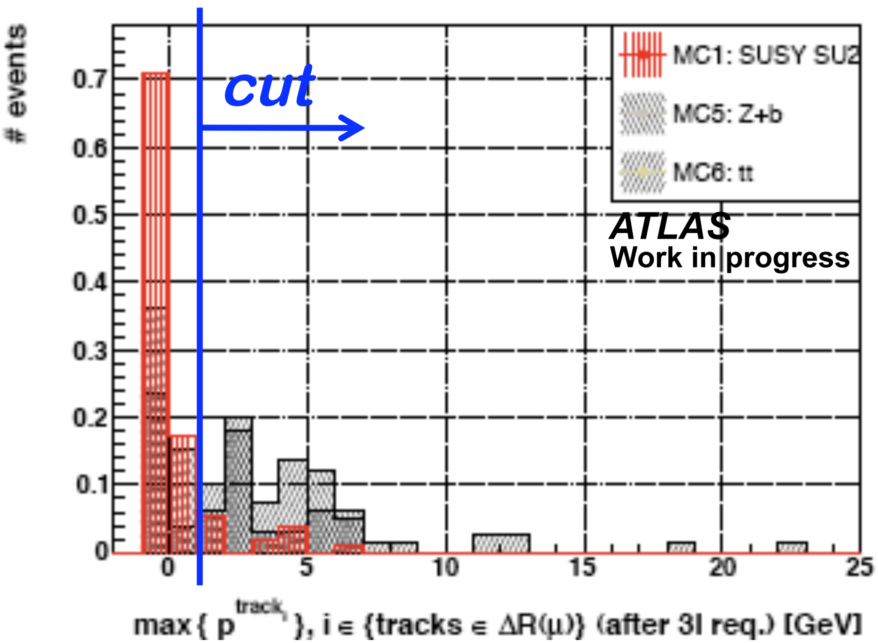
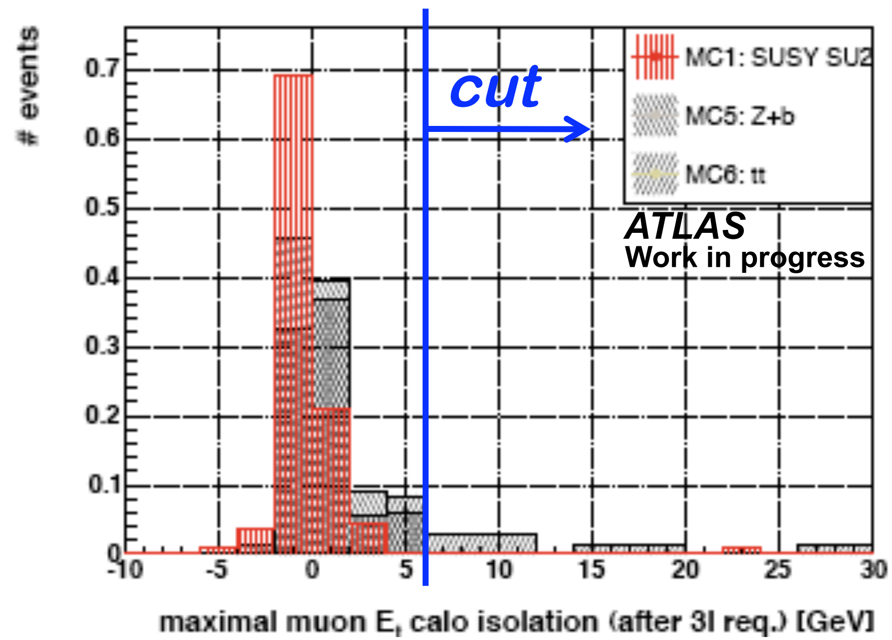


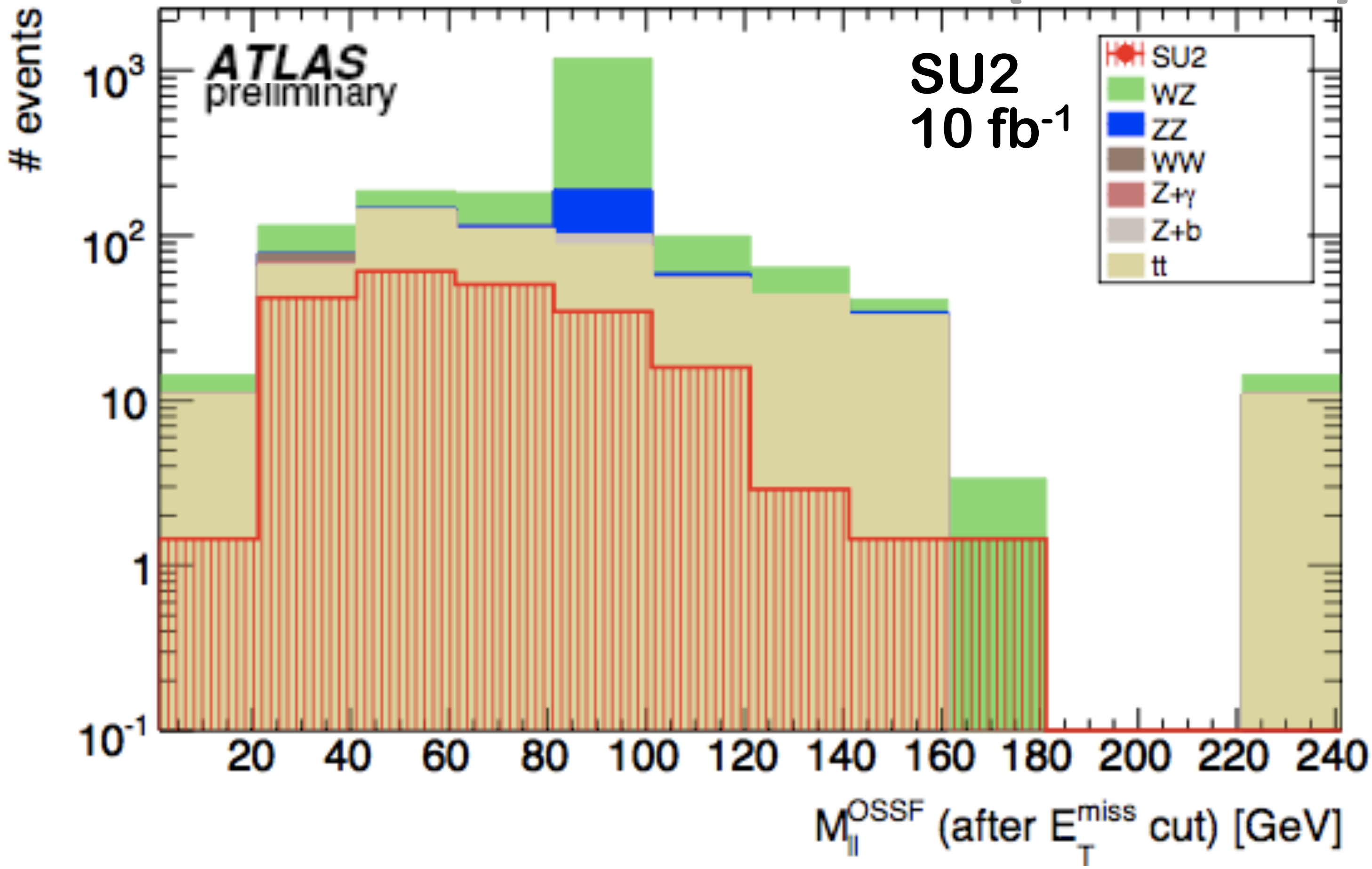




- Statistical significance improves almost by *O*(10)!

# Trilepton + Missing $E_T$: Selection (II)

- After the missing $E_T$ cut:

[arXiv:0901.0512]



# Trilepton Search: Reach (10 $fb^{-1}$)

- **Cut flow table:**

| Kinematic Cut | No Cuts | $N_L >= 2$ | OSSF | $N_L >= 3$ | TrackIsol | $m_{\ell\ell}$ | $E_T^{miss}$ | JetVeto |
|---|---|---|---|---|---|---|---|---|
| SU2 gauginos | 64.0k | 1647 | 1108 | 178 | 153 | 120 | 95 | 29 |
| SU2 other | 7081 | 776 | 353 | 127 | 95 | 85 | 82 | 0 |
| $t\bar{t}$ | 4.41M | 234k | 104k | 2812 | 634 | 507 | 476 | 42 |
| $ZZ$ | 38.2k | 10.4k | 9984 | 580 | 476 | 57 | 13 | 6 |
| $ZW$ | 156k | 17.2k | 14.5k | 1910 | 1682 | 322 | 218 | 154 |
| $WW$ | 400k | 22.7k | 10.7k | 25 | 8 | 8 | 8 | 8 |
| $Z\gamma$ | 32.8k | 7184 | 6970 | 91 | 27 | 7 | 3 | 0 |
| $Zb$ | 1.59M | 57.4k | 559k | 6523 | 2409 | 386 | 0 | 0 |
| inclusive SUSY $\mathscr{S}$ | | 2.60 | 1.74 | 2.76 | 3.36 | 5.31 | **5.94** | **1.87** |
| direct gaugino $\mathscr{S}$ | | 1.77 | 1.32 | 1.61 | 2.09 | 3.20 | **3.34** | **1.87** |

[arXiv:0901.0512]

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|---|---|---|---|---|---|---|---|---|
| SU2 gauginos | 64.0k | 1647 | 1108 | 178 | 153 | 120 | 95 | 29 |
| SU2 other | 7081 | 776 | 353 | 127 | 95 | 85 | 82 | 0 |
| $t\bar{t}$ | 4.41M | 234k | 104k | 2812 | 634 | 507 | 476 | 42 |
| $ZZ$ | 38.2k | 10.4k | 9984 | 580 | 476 | 57 | 13 | 6 |
| $ZW$ | 156k | 17.2k | 14.5k | 1910 | 1682 | 322 | 218 | 154 |
| $WW$ | 400k | 22.7k | 10.7k | 25 | 8 | 8 | 8 | 8 |
| $Z\gamma$ | 32.8k | 7184 | 6970 | 91 | 27 | 7 | 3 | 0 |
| $Zb$ | 1.59M | 57.4k | 559k | 6523 | 2409 | 386 | 0 | 0 |
| inclusive SUSY $\mathscr{S}$ | | 2.60 | 1.74 | 2.76 | 3.36 | 5.31 | **5.94** | **1.87** |
| direct gaugino $\mathscr{S}$ | | 1.77 | 1.32 | 1.61 | 2.09 | 3.20 | **3.34** | **1.87** |

$$\mathscr{S} = \frac{S}{\sqrt{S+B}}$$

[arXiv:0901.0512]

# Trilepton Search: Reach (10 fb$^{-1}$)

- Cut flow table:

| Kinematic Cut | No Cuts | $N_L >= 2$ | OSSF | $N_L >= 3$ | TrackIsol | $m_{\ell\ell}$ | $E_T^{miss}$ | JetVeto |
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[arXiv:0901.0512]

Expect $5\sigma$ with $\sim$80 fb$^{-1}$ (stat. only)

# Trilepton Search: Reach (10 $fb^{-1}$)

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[arXiv:0901.0512]

**Discovery with** 10 $fb^{-1}$ **possible!**

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[arXiv:0901.0512]

**Direct gaugino production more challenging**

# Trilepton Search: Reach (10 fb$^{-1}$)

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[arXiv:0901.0512]

- **Search equally sensitive to other benchmark points:**

| | SU1 | SU2 | SU3 | SU4 | SU8 |
|---|---|---|---|---|---|
| $\mathscr{S}$, 10 fb$^{-1}$ | 7.7 | 5.9 | 17.2 | 69.3 | 1.9 |
| $\int dt\,\mathscr{L}$ for $5\sigma$ | 4.2 | 7.1 | 0.8 | 0.1 | 70.5 |

[arXiv:0901.0512]

# Trilepton + Missing $E_T$: Triggering

- 3 leptons in the final state:
  - Can easily use lepton triggers!
- Identified optimal triggers for
  - Isolated electron (L2_e22i): $p_T^{e,\,\mathrm{iso}} > 25\,\mathrm{GeV}$
  - Isolated muon (L2_mu20): $p_T^{\mu,\,\mathrm{iso}} > 20\,\mathrm{GeV}$

| Selection Stage | SU2χ L2_e22i | SU2χ L2_mu20 | SU2χ ∪ | SU3χ L2_e22i | SU3χ L2_mu20 | SU3χ ∪ | SU3 incl. L2_e22i | SU3 incl. L2_mu20 | SU3 incl. ∪ |
|---|---|---|---|---|---|---|---|---|---|
| OSSF pair | 41% | 54% | 89% | 42% | 54% | 92% | 51% | 51% | 94% |
| OSSF+3$^{\mathrm{rd}}\ell$ | 58% | 67% | 93% | 59% | 63% | 95% | 66% | 68% | 98% |
| after all cuts | 57% | 66% | 92% | 58% | 57% | 94% | 66% | 64% | 97% |

[arXiv:0901.0512]

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SU2 direct gaugino production

Union of L2_e22i and L2_mu20

| Selection Stage | SU2χ L2_e22i | SU2χ L2_mu20 | SU2χ ∪ | SU3χ L2_e22i | SU3χ L2_mu20 | SU3χ ∪ | SU3 incl. L2_e22i | SU3 incl. L2_mu20 | SU3 incl. ∪ |
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| after all cuts | 57% | 66% | 92% | 58% | 57% | 94% | 66% | 64% | 97% |

[arXiv:0901.0512]

- Overall trigger efficiency for direct gaugino pair-production in SU2 after all cuts: 92%!

# Trilepton Search: Systematics for 10 fb$^{-1}$

| Source | Uncertainty: No jet veto | Uncertainty: With jet veto |
|---|---|---|
| Background production rates | 0.8% | 1.9% |
| Lepton Efficiency | 2.3% | 2.3% |
| Fakes ($R_{b\to\ell}$) | 4.0% | 1.2% |
| Hadronic energy scale | – | 1.8% |
| Missing energy scale | 1.5% | 1.0% |
| *Total systematic* | 4.9% | 3.8% |
| *Statistical* | 3.7% | 6.9% |
| *Statistical + Systematic* | 6.2% | 7.9% |

[arXiv:0901.0512]

- Background production rates: From statistical error on background
- Lepton Efficiency: Systematics on trigger + offline
- Fakes: See next slides
- Hadronic energy scale: Assume 5% error on JES

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[arXiv:0901.0512]

From statistical error on background

Systematics on trigger + offline

See next slides

Assume 5% error on JES

**Largest systematics < 5%!**

**Total systematics ~ 5%!**

# Understand Lepton Isolation from Data

- We don't know how well track and calorimeter isolation are modeled in MC:
  - Understand the rate of leptons from heavy flavour decays passing isolation requirements from data!

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- Classical Tevatron method:
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      - Restricted by the number of *b*-jets written to tape
      - Possible biases from *b*-physics triggers
    - If b-jet PDFs significant @LHC:
      - Gluon-b scattering to dijets!

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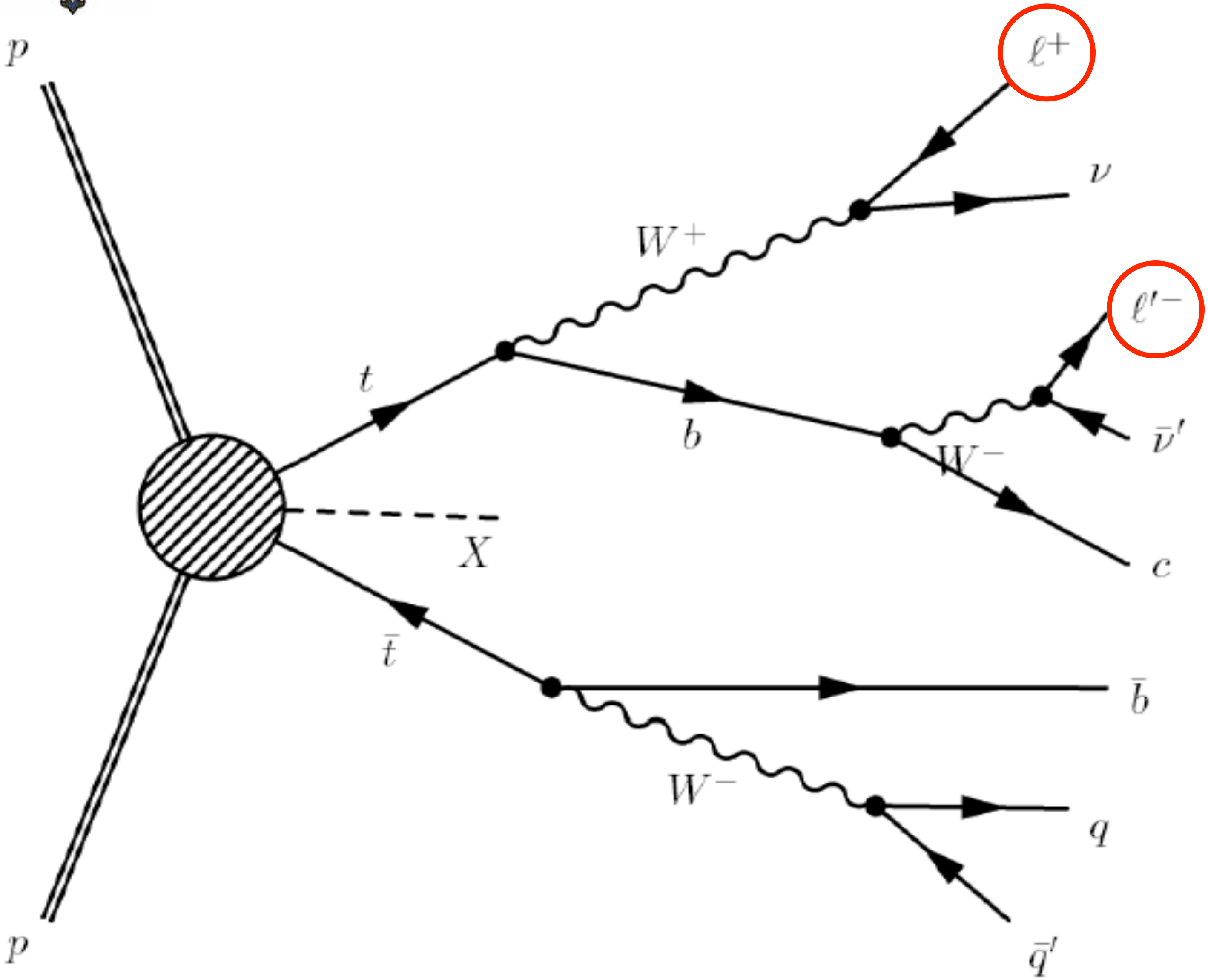
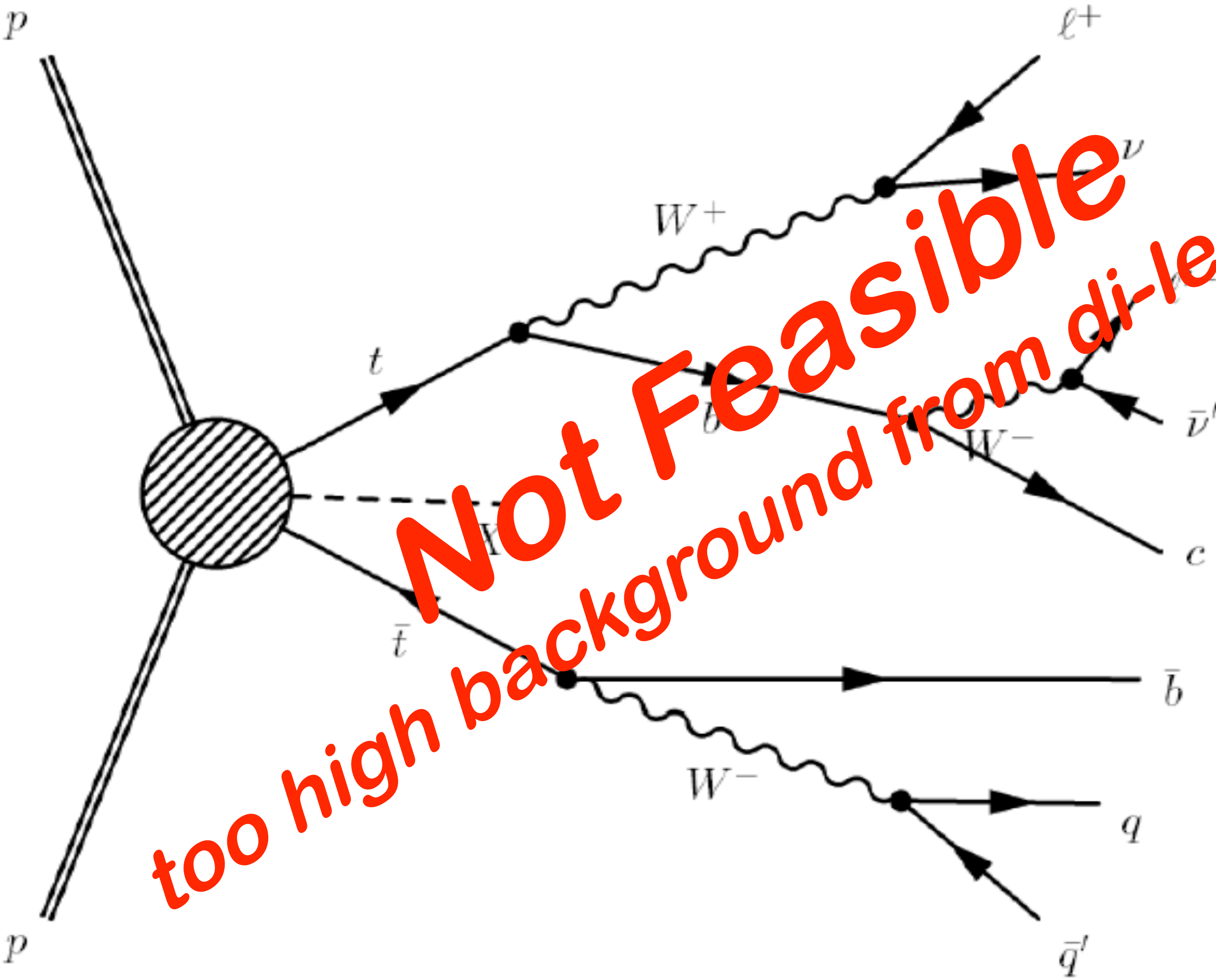
      - Possible biases from *b*-physics triggers
    - If b-jet PDFs significant @LHC:
      - Gluon-b scattering to dijets!
- Our proposal for the LHC:
  - Use semileptonic *tt* events:
    - Rate-to-tape may be higher than for *b*-physics
    - No need to rescale the $p_T$ spectrum of *b*-jets
    - More handles to tag an event with a *b*-jet w/o using it

# Understand Lepton Isolation from Data




***Opposite charge***

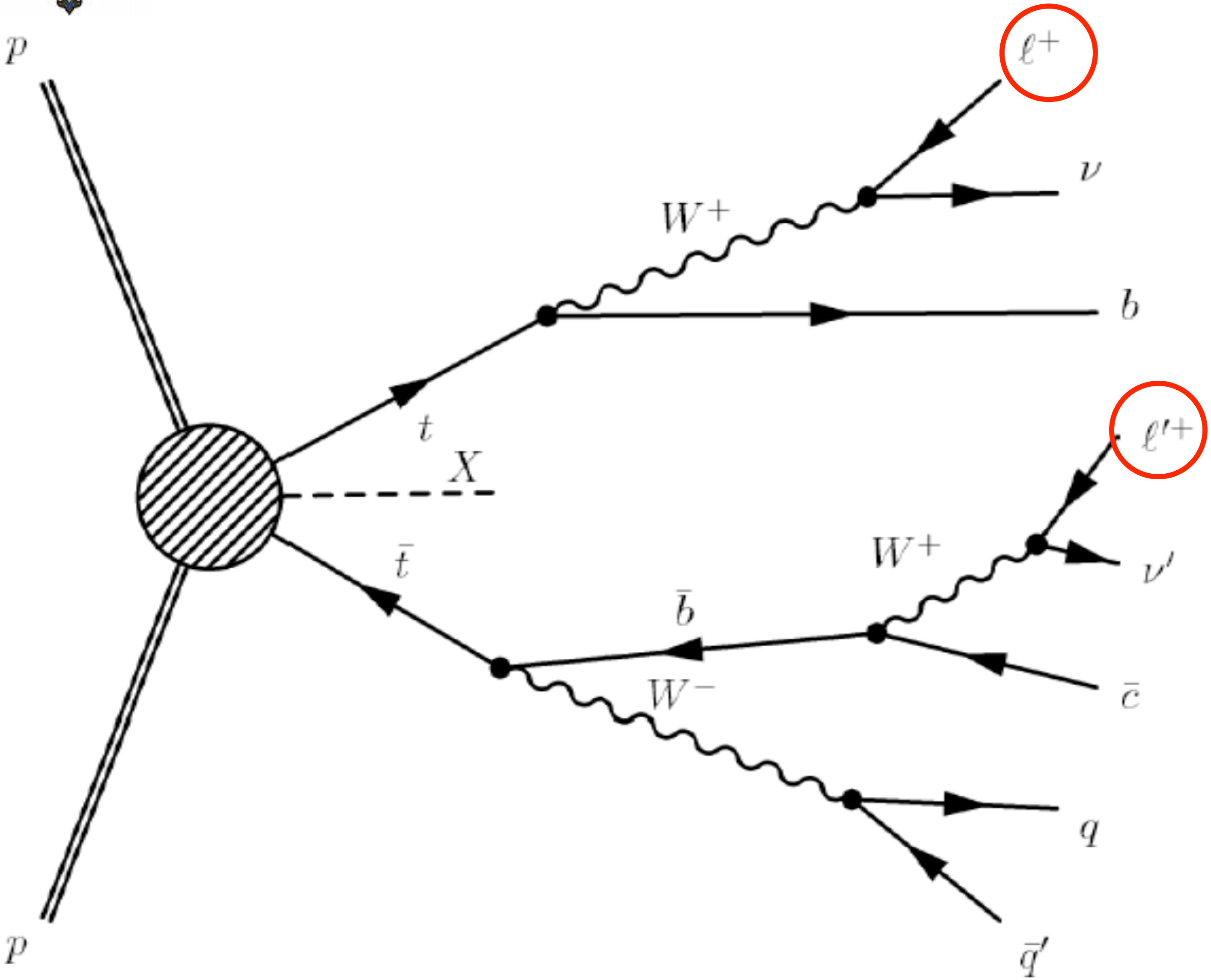
# Understand Lepton Isolation from Data




**Not Feasible**

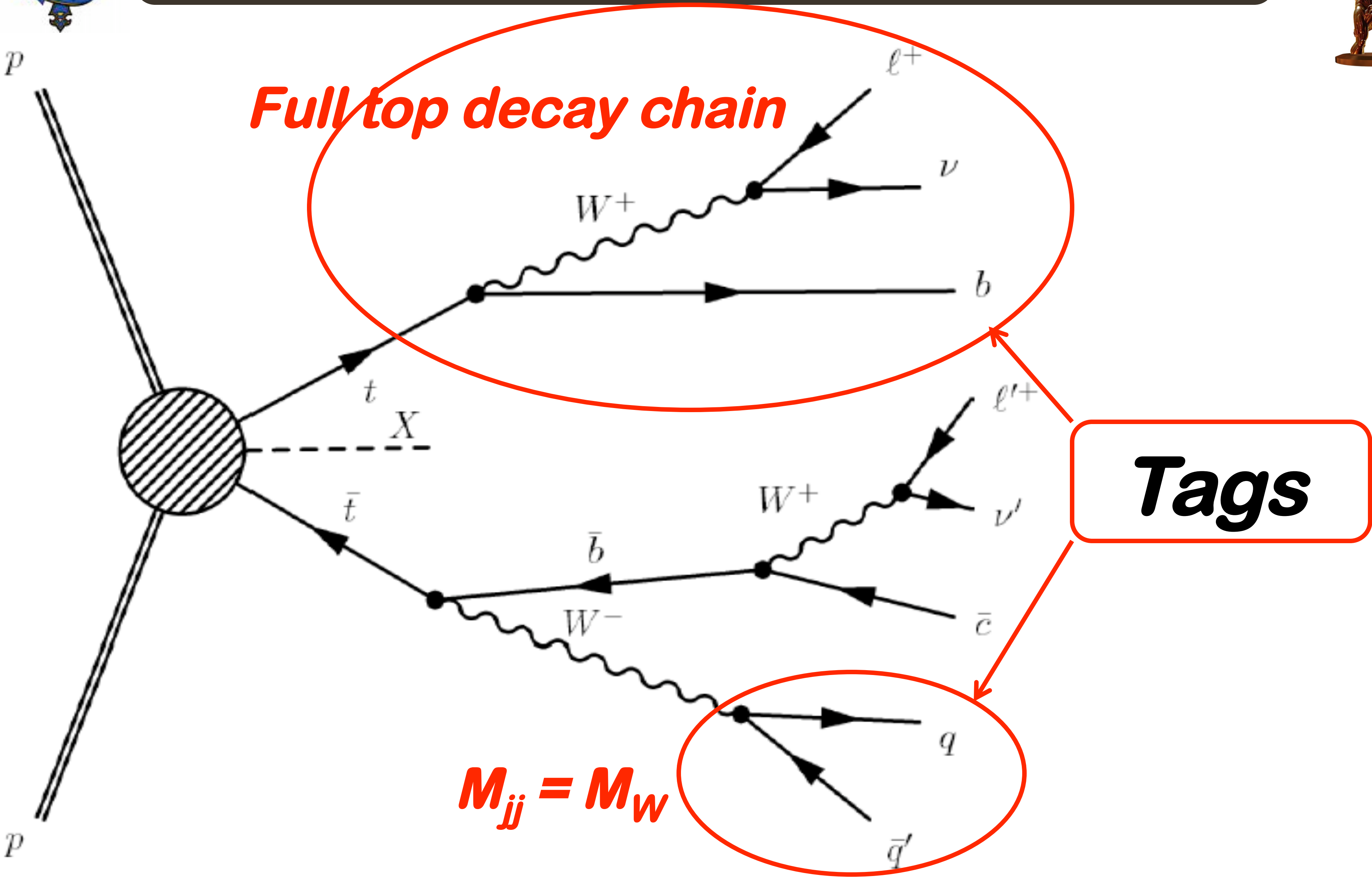
*too high background from di-leptonic tt*

# Understand Lepton Isolation from Data




**Same charge**

# Understand Lepton Isolation from Data



# Summary

- LHC is *the* BSM discovery machine!
- ATLAS commissioning + alignment progressing well!
- Trilepton + missing $E_T$ final states:
  - Very interesting in BSM context:
    - Higgsless models
    - Supersymmetry
      - especially with "heavy" strong interacting sparticles!
  - Leptons experimentally "easy"
  - Track + calorimeter isolation!
  - For inclusive SU2 production, a 5 sigma discovery appears to be possible with 10 $fb^{-1}$
  - Triggering strategy OK
- Suggested new approach for the LHC:
  - measure the rate of leptons from leptonic *b*-decays passing isolation criteria in *tt* events!

# Outlook

- Proceed with the commissioning of ATLAS
- Investigate the same sign dilepton + X signature
- Validate the method to measure the rate of leptons from leptonic *b*-decays passing isolation criteria in *tt* events!

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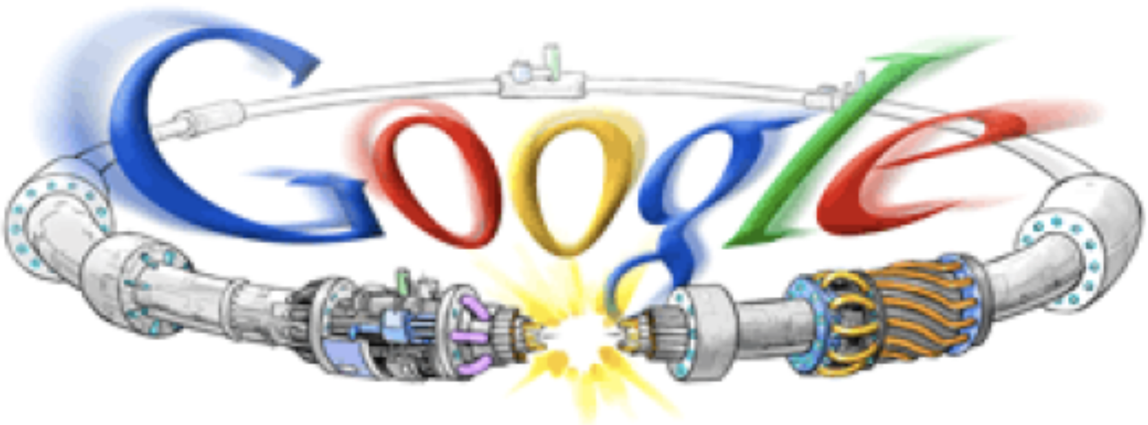
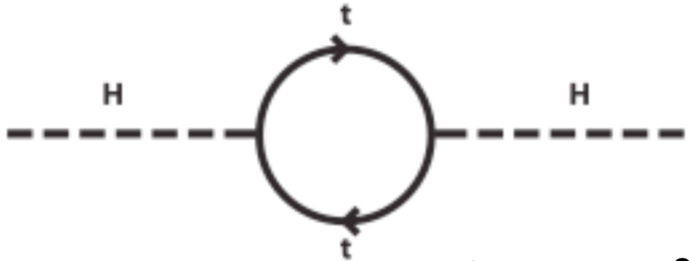



- Measure everything in data!
- First exclusion limits feasible with 0.5 $fb^{-1}$!

# Backup

# SUSY: the Cure for the Diseases?

- In the SM, we are presented with the Hierarchy problem:
  - Higgs has S=0
  - Therefore immense virtual loop corrections to Higgs mass:




$$\text{SM}: \Delta M_H^2 \sim \Lambda_{UV}^2$$

  - Finetuning at about $10^{-32}$ level!
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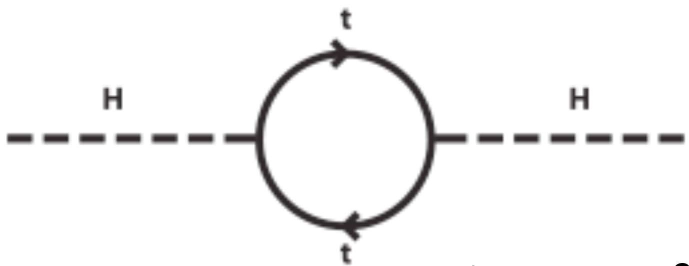
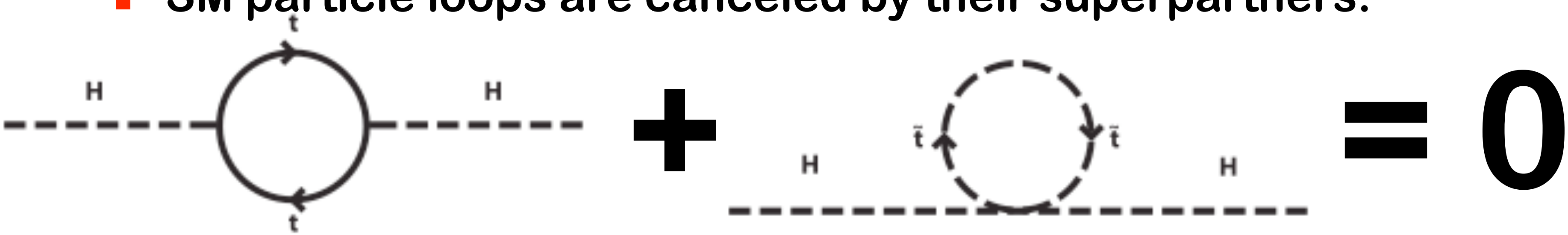


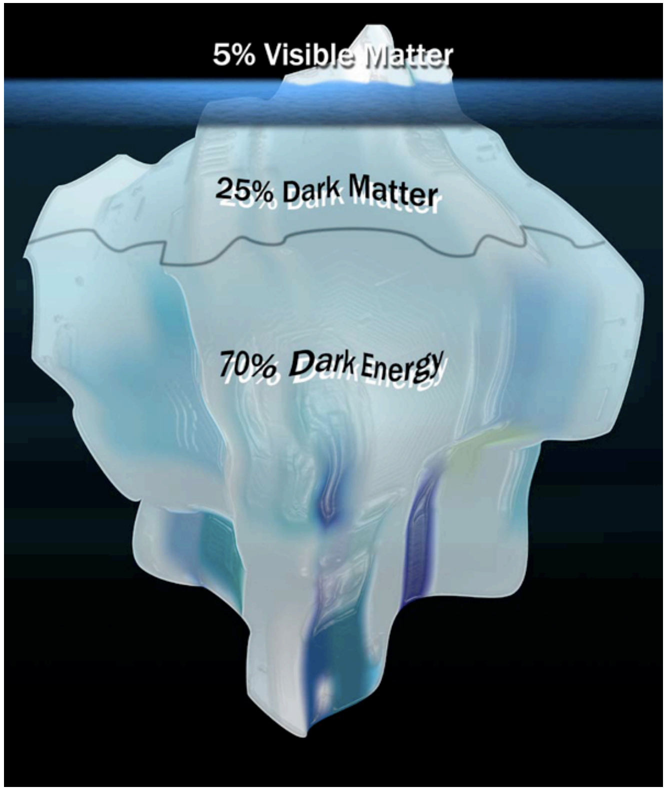

$$\mathbf{SM :}\ \Delta M_H^2 \sim \Lambda_{UV}^2$$

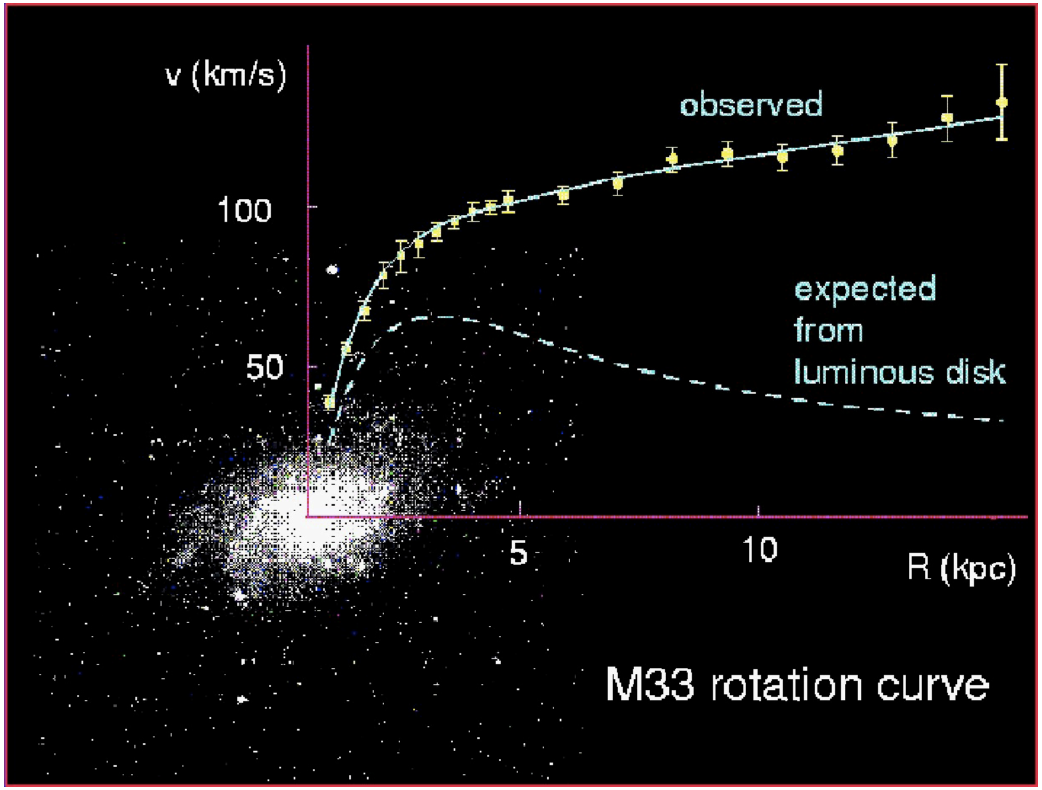
  - Finetuning at about $10^{-32}$ level!
    - Strictly speaking, Higgs mass not calculable in SM framework!
- SUSY:
  - postulate a superpartner for each particle of the SM!
    - Same quantum numbers, but spin different by ½
  - SM particle loops are canceled by their superpartners:



# SUSY: the Cure for the Diseases?

- We see only a small fraction of mass in Universe:

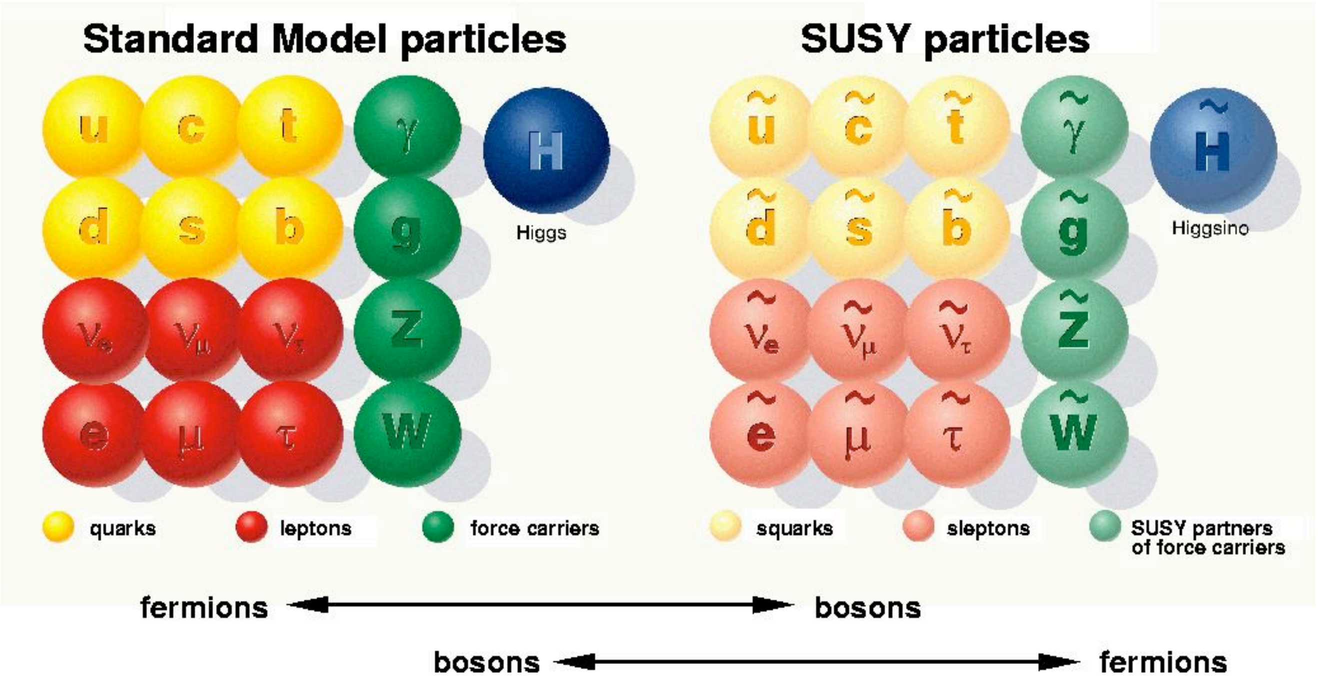



- The Lightest Supersymmetric Particle (LSP):
  - excellent candidate for Dark Matter!

# SUSY in a Nutshell

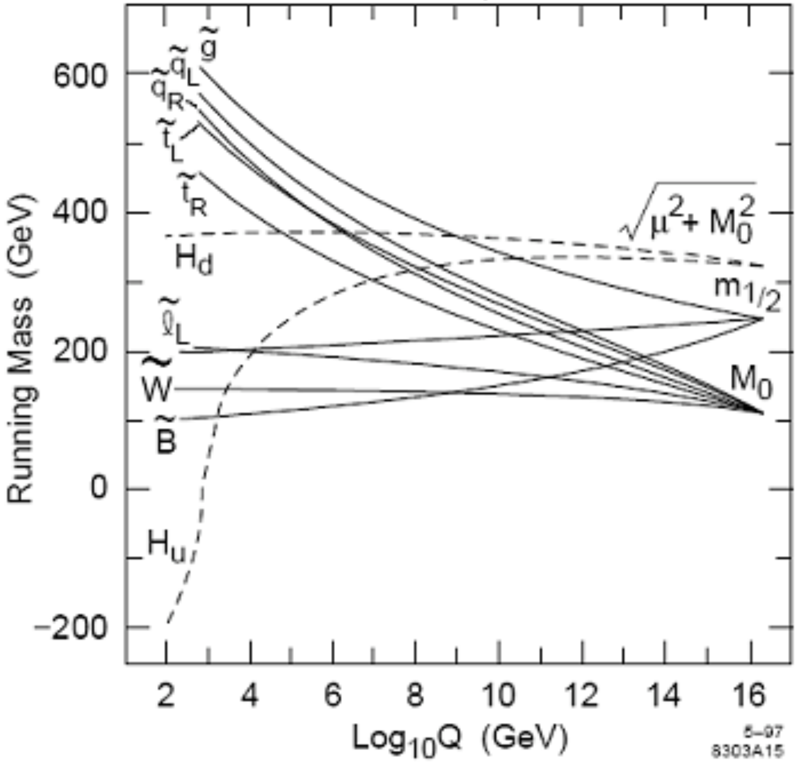
- **Minimal version of SUSY:**
  - **Exactly one superpartner for each SM particle:**




  - **Higgs sector to be extended:**
    - 5 Higgses: $h^0$, $H^0$, $H^{+/-}$, $A^0$

# SUSY in a Nutshell

- Masses of SM particles ≠ masses of superpartners
  - SUSY must be spontaneously broken!
  - There are few mechanisms for “soft” SUSY breaking:
    - SUGRA
    - GMSB
    - AMSB
    - …
  - SUGRA: too many parameters!
  - mSUGRA:
    - Assumption: unification of parameters at GUT scale
    - 5 parameters only!
    - However, decent phenomenological richness!
    - Superparticle spectra via evolution from GUT to EW scale
    - + matching to precision measurements like WMAP, $g_\mu$-2, etc.



# SUSY in a Nutshell

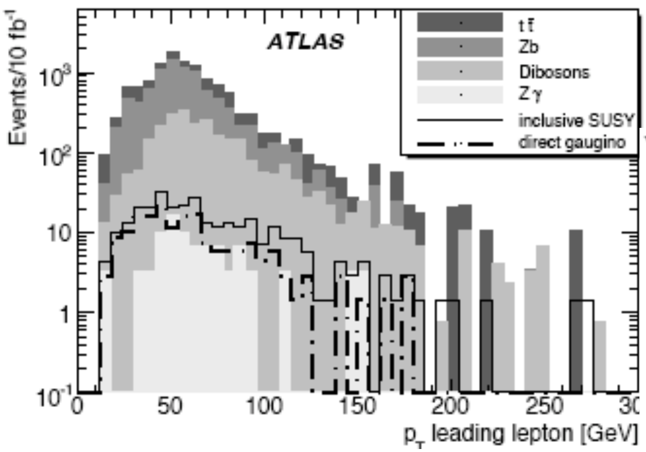
- We know:
  - $\tau_{proton} > 10^{32}$ s
- It is reasonable to assume:
  - Dark matter candidate stable
- Both imply:
  - R-parity conservation ($R = (-1)^{3(B-L)+2S}$)
- Focus on R-parity conserving models today
  - Generic prediction:
    - Significant missing $E_T$ due to LSPs escaping detection!

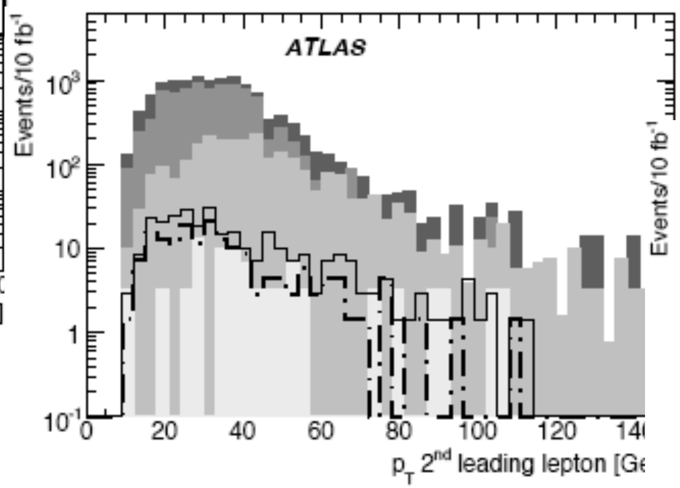
# Tri-lepton + Missing $E_T$: Preselection

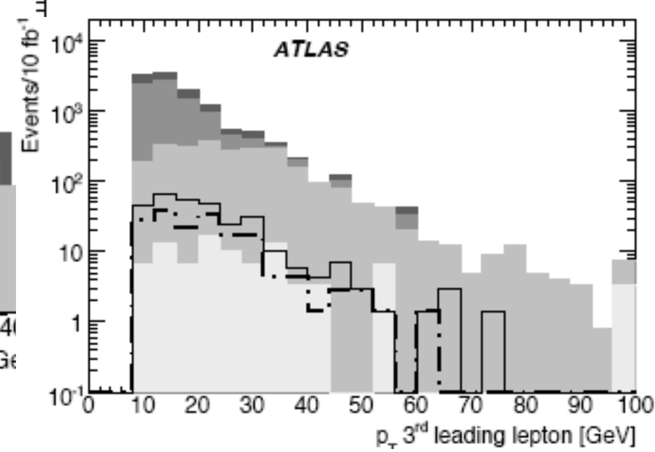
- **Trigger:** $p_T^{e,\,\mathrm{iso}} > 25\,\mathrm{GeV}$ **OR** $p_T^{\mu,\,\mathrm{iso}} > 20\,\mathrm{GeV}$
- **Lepton preselection:**

| | Muon | Electron | Jet |
|---|---|---|---|
| $p_\mathrm{T}$ cut | $> 10$ GeV | $> 10$ GeV | $> 10$ GeV |
| $\eta$ cut | $\lvert\eta\rvert < 2.5$ | $\lvert\eta\rvert < 1.37$ or $1.52 < \lvert\eta\rvert < 2.5$ | $\lvert\eta\rvert < 2.5$ |
| Calorimeter Isolation | $\lvert E\rvert < 10$ GeV in $\Delta R = 0.2$ | $\lvert E\rvert < 10$ GeV in $\Delta R = 0.2$ | - - |

- **Resulting lepton distributions:**



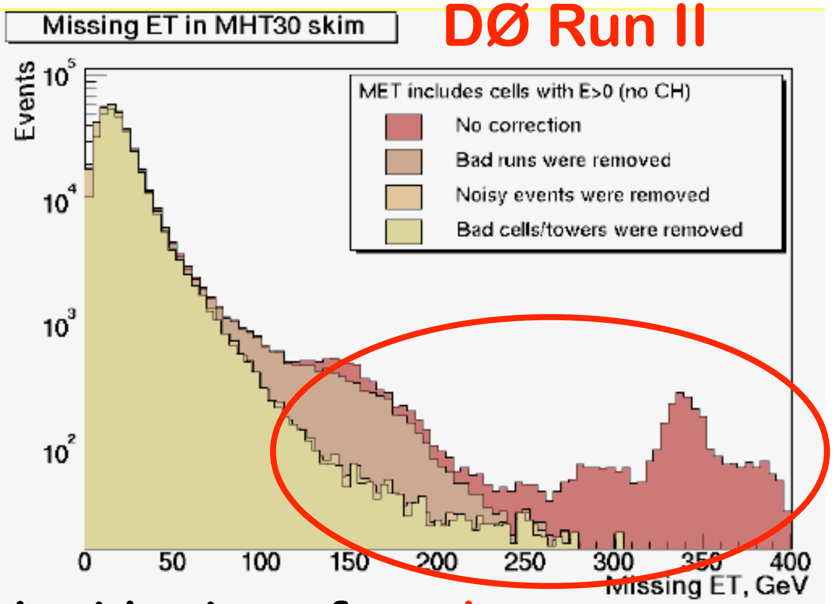



# Why Are Leptonic Final States Interesting for BSM Searches?

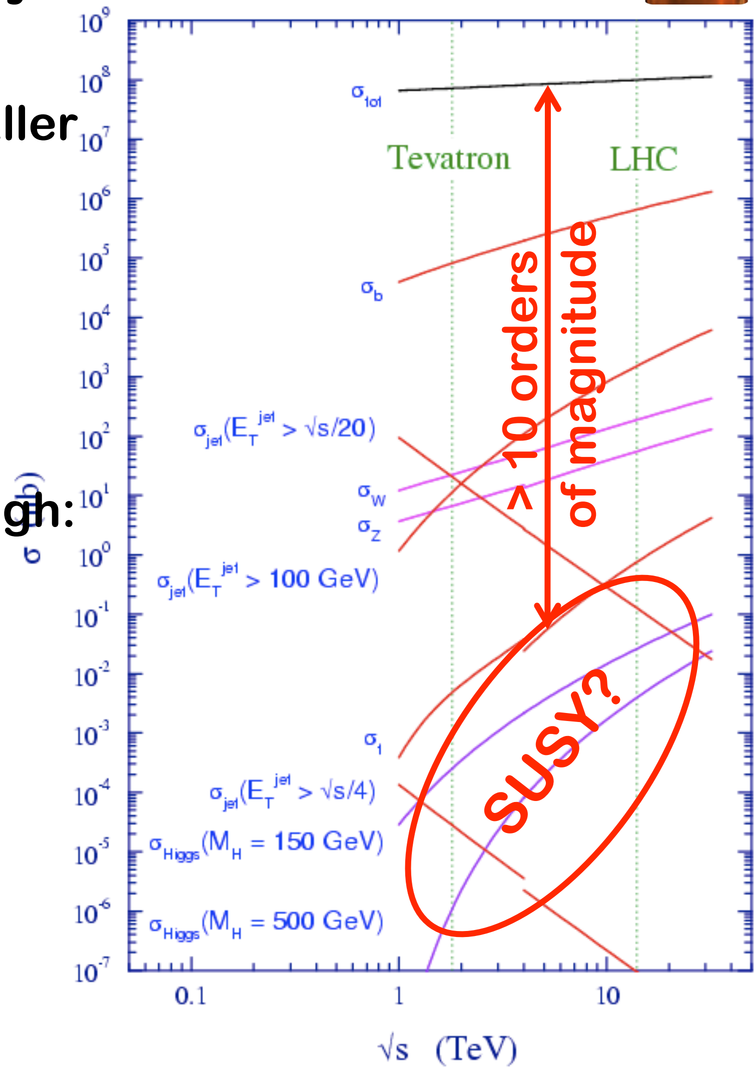
- Leptons are "easier" to measure:
  - Efficiencies are easier to understand
  - Smaller uncertainties (e.g. no Jet Energy Scale (JES))
  - Can be well understood earlier on!
- Indirect advantages:
  - Can cut on lower missing $E_T$ values
    - Missing $E_T$ = $\Sigma$ (detector problems)
    - Missing $E_T$ problems in the tails!
    - Typically, missing $E_T$ problems when energetic jet mismeasured
- However:
  - May need track / calo isolation to reject leptons from heavy flavour decays
  - Isolation typically badly modeled in MC
    - Need to determine lepton rates from heavy flavour from data!

DØ Run II



# Why Are Leptonic Final States Interesting for BSM Searches?

- Leptons can be used to reject QCD junk at the LHC:
  - Trigger level:
    - Lepton rates intrinsically much smaller
      - Lepton trigger intrinsically more pre-scale safe!
    - Avoid potential biases to event selection!
  - Offline analysis level:
    - Significantly less data to plow through:
      - Will become an issue at higher luminosities!
- Once BSM discovered:
  - Identify model (SUSY, UED, ...)
  - Measure particle spectrum:
    - Leptonic final states are clean
    - Can be measured more precisely!

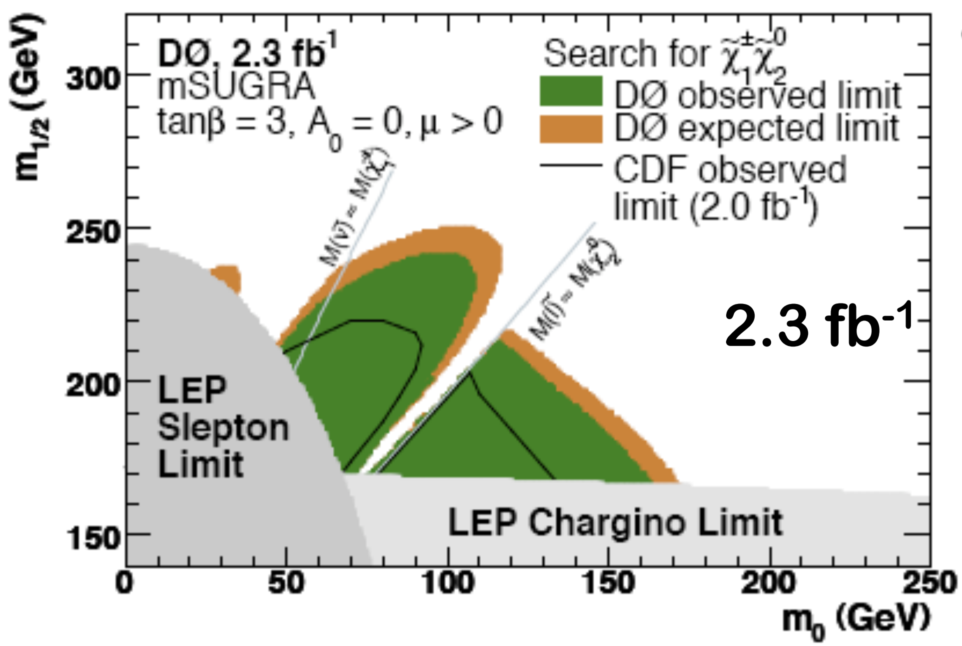


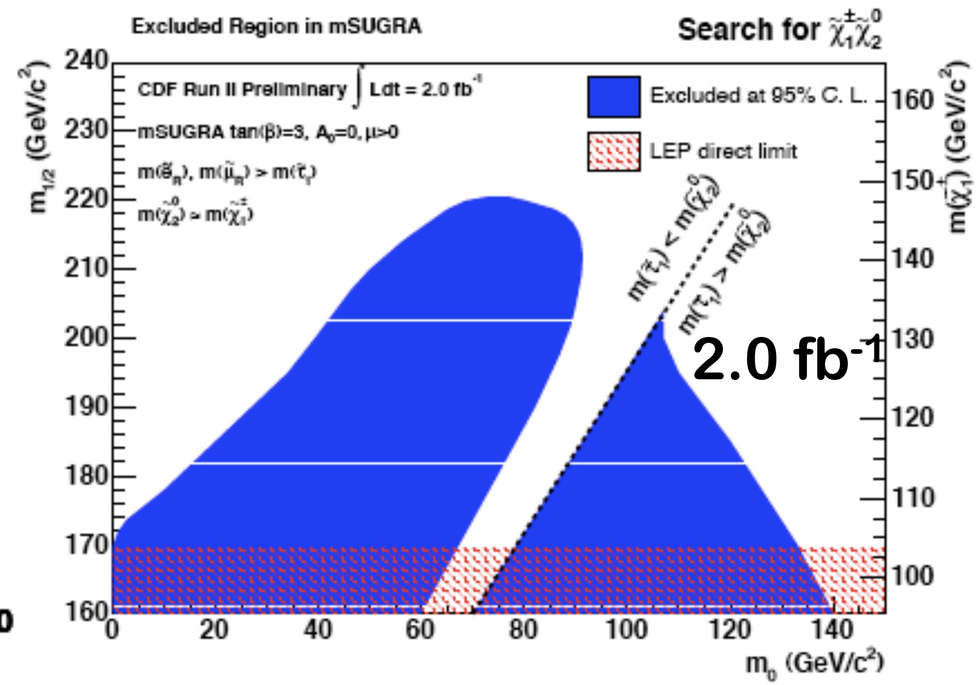
# Tri-leptons on the Other Side of the Pond

- 3l + missing $E_T$ signature: long tradition at the Tevatron
  - Dubbed “Golden channel”

**DØ**: search for 3l + missing ET + X
Uses 3l and 2l + track

**CDF**: search for 3l + missing $E_T$ + X
Uses 3l and 2l + track




- Very similar philoshophy
  - Differences in the small print